

TRANSPORT PROPERTIES OF NITROGEN,  
HYDROGEN, OXYGEN, AND AIR TO 30,000°K

Prepared by

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RESEARCH AND ADVANCED DEVELOPMENT DIVISION  
AVCO CORPORATION  
Wilmington, Massachusetts

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AIR FORCE SYSTEMS COMMAND  
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Wright-Patterson Air Force Base, Ohio

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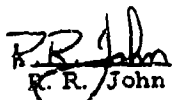
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APPROVED

  
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ABSTRACT

The viscosity, thermal conductivity, electrical conductivity, binary diffusion coefficients, and total radiated power in the continuum have been calculated for hydrogen, nitrogen, oxygen, and air for temperatures from 1000 to 30,000°K and for pressures from 1 to 30 atm. The viscosity, electrical and thermal conductivities, and diffusion coefficients were calculated from the first Chapman-Enskog approximation<sup>1,2</sup> using the best available cross-section data from the literature. Coulomb collisions were treated approximately by means of effective collision cross sections, chosen to make the calculated transport properties agree with the results of Spitzer and Härm<sup>3</sup> for the fully ionized case. Effects of ambipolar diffusion and charge exchange were included in the calculation. The continuum radiated power was calculated from Kramers' semiclassical approximation<sup>4</sup> with an empirical correction factor to make the results agree with the limited experimental data available in the range of interest.

The calculated transport properties agree well with the results of Mason, et al,<sup>5-7</sup> at low temperatures and of Spitzer and Härm<sup>3</sup> at high temperatures, but in the intermediate temperature range, from about 10,000 to 20,000°K, the results differ rather significantly from the results obtained by previous investigators. The major difference is in the reaction thermal conductivity due to ionization, where the inclusion of charge exchange results in a thermal conductivity almost an order of magnitude lower than that obtained in most previous calculations.

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## I. INTRODUCTION

In connection with current Avco RAD studies on the electric-arc positive column and on re-entry problems, it was found necessary to have reasonably accurate values for the transport properties of various gases at high temperatures. The experimental measurement of the transport properties of gases is very difficult for temperatures above about 2000°K, so that up to the present time most of our knowledge of the transport properties in this temperature range has had to be obtained from kinetic theory calculations.<sup>1-2</sup> A considerable number of such calculations have been made in the past for various high-temperature gases,<sup>5-32</sup> and a review of some of the work on air is given in references 5 and 15. Unfortunately, however, accurate information on the required atomic- and molecular-collision cross sections at high temperatures has generally not been available until quite recently, so that many of the earlier calculations are seriously in error, because of incorrect values used for some of the required collision cross sections. For example, in the case of air,<sup>5</sup> the uncertainty in the cross sections has led to a difference of as much as a factor of 2, or more, in the values of the transport properties calculated by different investigators. This situation is rapidly changing, however, and it is now possible to obtain rather accurate values for many of the required cross sections,<sup>6, 33, 34</sup> so that the transport properties of high-temperature gases can now be calculated with considerably greater accuracy than has been possible in the past.<sup>5-7, 33</sup> In view of this situation, it seemed desirable to undertake a systematic recalculation of the relevant gas transport properties, using the latest available data for the required collision cross sections.

The present memorandum is a preliminary report on Avco RAD's calculations of the transport properties of various gases at high temperatures. In this work, it was not attempted to make any extensions of present theory, but simply to calculate the transport properties as accurately as possible using presently available methods and data. The details of the calculational procedure are described, and results are presented for hydrogen, nitrogen, oxygen, and air for temperatures from 1000 to 30,000°K and pressures from 1 to 30 atm. The properties included in the calculation are the electrical conductivity, thermal conductivity, viscosity, binary-diffusion coefficients, and total continuum radiation (line and band spectral radiation has not been included).

## II. DISCUSSION

### A. TRANSPORT PROPERTY FORMULAS

The calculations of the electrical and thermal conductivities, viscosity, and diffusion coefficients are based on the first Chapman-Enskog approximation, summarized in reference 1. This approximation gives explicit formulas for the transport properties in terms of certain "collision integrals"  $\pi \bar{\Omega}_{ij}^{(l,s)}$ , defined in reference 6, which describe the interaction between molecules of species  $i$  and  $j$ , and which have the physical significance of an effective cross section for collisions between molecules  $i$  and  $j$ . Specifically, the collision integrals  $\pi \bar{\Omega}_{ij}^{(l,s)}$  are defined as weighted averages of the collision cross sections of the form

$$\pi \bar{\Omega}_{ij}^{(l,s)} = \frac{\int_0^\infty \int_0^\pi \exp(-\gamma^2) \gamma^{2s+3} (1 - \cos^l \chi) 4\pi \sigma_{ij} \sin \chi \, d\chi \, d\gamma}{\int_0^\infty \int_0^\pi \exp(-\gamma^2) \gamma^{2s+3} (1 - \cos^l \chi) \sin \chi \, d\chi \, d\gamma} \quad (1)$$

where  $\sigma_{ij} = \sigma_{ij}(\chi, g)$  is the differential scattering cross section for the pair  $i-j$ ,  $\chi$  is the scattering angle in the center of mass system,  $g$  is the relative velocity of the colliding particles, and  $\gamma = \sqrt{\frac{m_i m_j}{2(m_i + m_j)kT}} g$  is the reduced velocity. The collision integrals  $\pi \bar{\Omega}_{ij}^{(l,s)}$  defined in this way differ from the integrals  $\Omega_{ij}^{(l,s)}$  defined in reference 1 only in the normalization factor occurring in the definition (1).

In this work, the complete kinetic-theory formulas for the transport properties given in reference 1 were not used, but instead the formulas were approximated by the following relations: 25, 35, 36

1. Viscosity  $\mu$ ,

$$\mu = \sum_{i=1}^n \left[ m_i x_i / \left( \sum_{j=1}^n x_j \Delta_{ij}^{(2)} \right) \right] \quad (2)$$

2. Thermal conductivity  $K$ ,

$$K = K_{tr} + K_{int} + K_r \quad (3)$$

where the translational thermal conductivity

$$K_{tr} = \frac{15}{4} k \sum_{i=1}^n \left[ x_i / \left( \sum_{j=1}^n a_{ij} x_j \Delta_{ij}^{(2)} \right) \right] \quad (4)$$

the internal thermal conductivity

$$K_{int} = k \sum_{i=1}^n \left[ \left( \frac{c_{pi}}{R} - \frac{5}{2} \right) x_i / \left( \sum_{j=1}^n x_j \Delta_{ij}^{(1)} \right) \right] \quad (5)$$

and the reaction thermal conductivity\*

$$K_r = k \sum_{l=1}^m \frac{(\Delta H_l / RT)^2}{\sum_{i=1}^n (n_{li} / x_i) \sum_{j=1}^n (n_{lj} x_j - n_{lj} x_i) \Delta_{ij}^{(1)}} \quad (6)$$

\*Note that this formula already includes the effects of ambipolar diffusion on the reaction conductivity of an ionized gas.

3. Electrical conductivity  $\sigma$ ,

$$\sigma = (e^2/kT) \left( z_0 / \sum_{j=1}^n z_j \Delta_{ej}^{(1)} \right) \quad (7)$$

where the prime on the summation sign indicates that the term  $z_0 \Delta_{ee}^{(1)}$  is omitted from the sum,

4. Binary diffusion coefficient  $D_{ij}$ ,

$$D_{ij} = (kT)/(p \Delta_{ij}^{(1)}) \quad (8)$$

In the above equations,

$$\Delta_{ij}^{(1)} = \frac{8}{3} \sqrt{\frac{2 m_i m_j}{\pi kT (m_i + m_j)}} \pi \bar{n}_{ij}^{(1,1)} \quad (9a)$$

$$\Delta_{ij}^{(2)} = \frac{16}{5} \sqrt{\frac{2 m_i m_j}{\pi kT (m_i + m_j)}} \pi \bar{n}_{ij}^{(2,2)} \quad (9b)$$

and

$$a_{ij} = 1 + \frac{[1 - (m_i/m_j)] [0.45 - 2.54 (m_i/m_j)]}{[1 + (m_i/m_j)]^2} \quad (10)$$

where

$m_i$  is the mass of a particle of species  $i$

$z_i$  is the mole-fraction of species  $i$

$c_{pi}$  is the specific heat per mole at constant pressure for species  $i$

$n$  is the total number of species present in the system,  
the  $a_{li}$  are the stoichiometric coefficients in the  $l^{\text{th}}$  chemical  
reaction written in the balanced form  $\sum_{i=1}^n a_{li} X^{(i)} = 0$

$\Delta H_l = \sum_{i=1}^n n_{li} H_i$  is the heat of reaction per mole for the  $l^{\text{th}}$  reaction

$m$  is the total number of independent reactions occurring in the system

$k$  is Boltzmann's constant

$R$  is the universal gas constant

$e$  is the electronic charge

$p$  is the pressure.

Although still somewhat complicated, equations (2) through (10) above are much simpler than the equations given by the first Chapman-Enskog approximation<sup>1</sup> and give results within a few percent of the latter, in most cases.<sup>25, 35</sup>

Since the collision integrals  $\pi \bar{\Omega}_{ij}^{(l,s)}$  are known within only about 10 to 20 percent at best, the additional error introduced in our results by using the approximate equations (2) through (10) in place of the complete first Chapman-Enskog approximation is negligible.

The effects of Coulomb collisions are not given very accurately by the first Chapman-Enskog approximation; for example, in the limiting case of a fully ionized gas, the transport properties calculated from this approximation differ by about a factor of 2 from those obtained from an accurate solution of the Boltzmann equation.<sup>3, 37, 38</sup> Several authors<sup>3, 37-40</sup> have suggested more accurate approximations for treating the effects of Coulomb collisions, but a complete solution of the problem has apparently not yet been given for a gas of arbitrary degree of ionization. In the present work, interpolation was effected through the region of partial ionization by means of equations (2) through (10) using effective Coulomb collision cross sections  $\pi \bar{\Omega}_{ij}^{(l,s)}$  chosen to make the calculated transport properties agree as closely as possible with the results of Spitzer and Härm<sup>3</sup> for the fully ionized case.

## B. CONTINUUM RADIATION FORMULA

The total continuum radiated power per unit volume  $P_r$  was estimated from Kramers' semiclassical approximation<sup>4</sup>

$$P_r = \gamma \frac{64 \pi^{3/2} e^6 p^2 \Delta\nu}{3 \sqrt{6} m_e^{3/2} c^3 (kT)^{5/2}} \sum_{i=1}^n x_i Z_i^2 \quad (11)$$

where

- $\Delta\nu$  is the bandwidth of the spectrum, assumed equal to the width  $\Delta\nu_B = 4kT/h$  of the blackbody distribution
- $c$  is the velocity of light
- $h$  is Planck's constant
- $Z_i e$  is the effective ionic charge of the species  $i$  for radiative collisions with electrons
- $\gamma=3$  is an empirical constant introduced in order to make the calculated values of the total radiated power  $P_r$  agree as well as possible with the limited experimental data available at high pressures.<sup>41-42</sup>

Molecular-band and atomic-line radiation were not included in the calculation, since these processes generally make a negligible contribution to the total radiated power at the very high temperatures for which radiative heat losses are important in the overall energy balance.

### C. COLLISION CROSS SECTIONS

The transport properties of hydrogen, nitrogen, oxygen, and air at temperatures from 1000 to 30,000°K and pressures from 1 to 30 atm have been computed from equations (2) through (11), using a program which has been set up for the Philco 2000 digital computer. The species included in the calculations were as follows: for hydrogen,  $H_2$ ,  $H$ ,  $H^+$ , and  $e$ ; for nitrogen,  $N_2$ ,  $N$ ,  $N^+$ ,  $N^{++}$ , and  $e$ ; for oxygen  $O_2$ ,  $O$ ,  $O^+$ ,  $O^{++}$ , and  $e$ ; for air,  $N_2$ ,  $N$ ,  $N^+$ ,  $N^{++}$ ,  $O_2$ ,  $O$ ,  $O^+$ ,  $NO$ ,  $NO^+$ , and  $e$ . The equilibrium gas composition was taken from references 43 and 44 while the thermodynamic functions  $H_i$  and  $c_{pi}$  for the individual species were obtained from internal calculations at Avco RAD.<sup>45, 46</sup>

The required collision integrals  $\bar{\Omega}_{ij}^{(l, s)}$  were obtained from a fairly extensive survey of the literature and are shown in figures 1 through 4. The solid curves in these figures indicate cross sections for which fairly reliable data were found in the literature, while the dashed curves are estimated cross sections for the cases where good data are not available. Since the accuracy of the calculated transport properties is largely determined by the accuracy of the

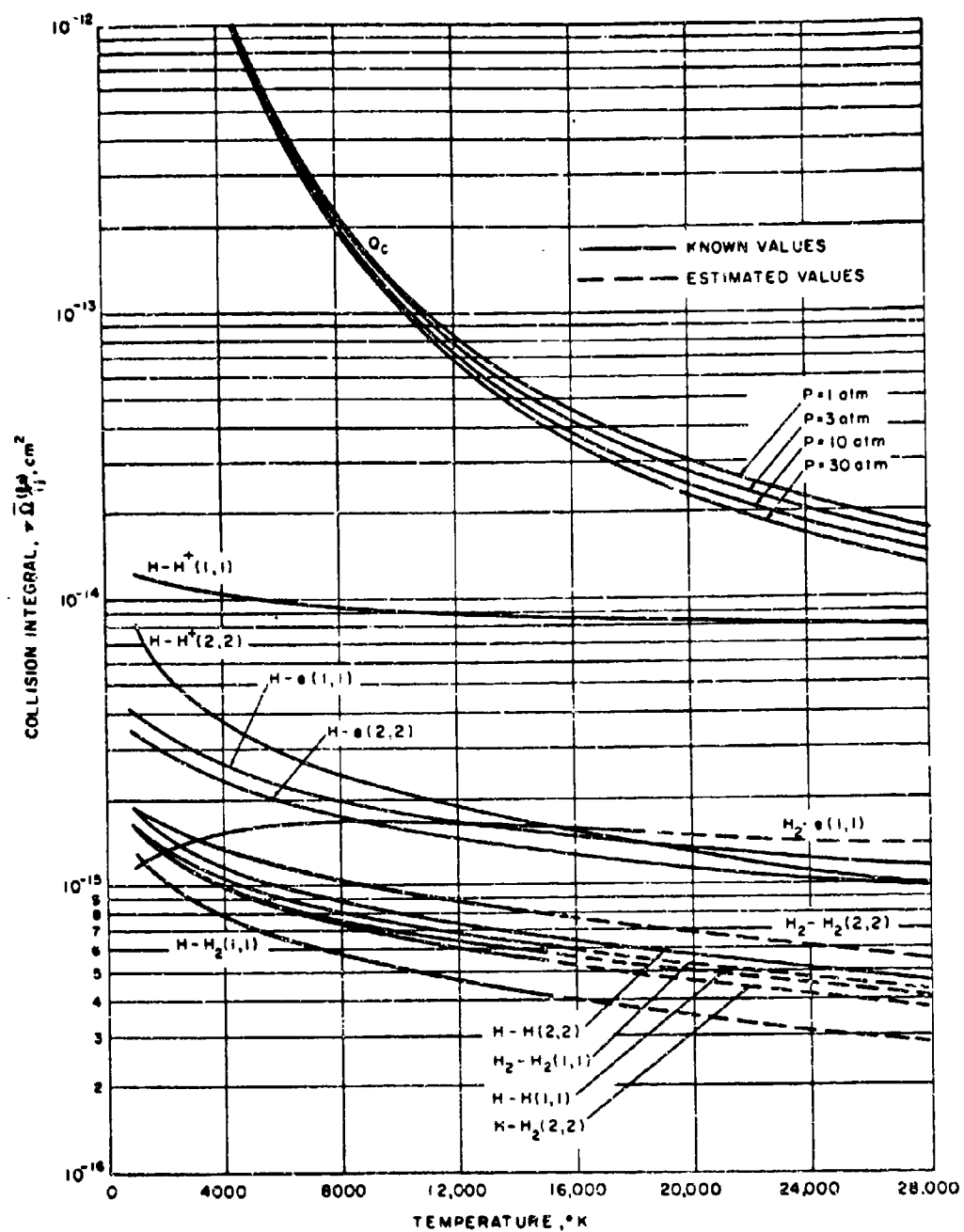


Figure 1 COLLISION INTEGRALS FOR HYDROGEN VERSUS TEMPERATURE  
62-1731

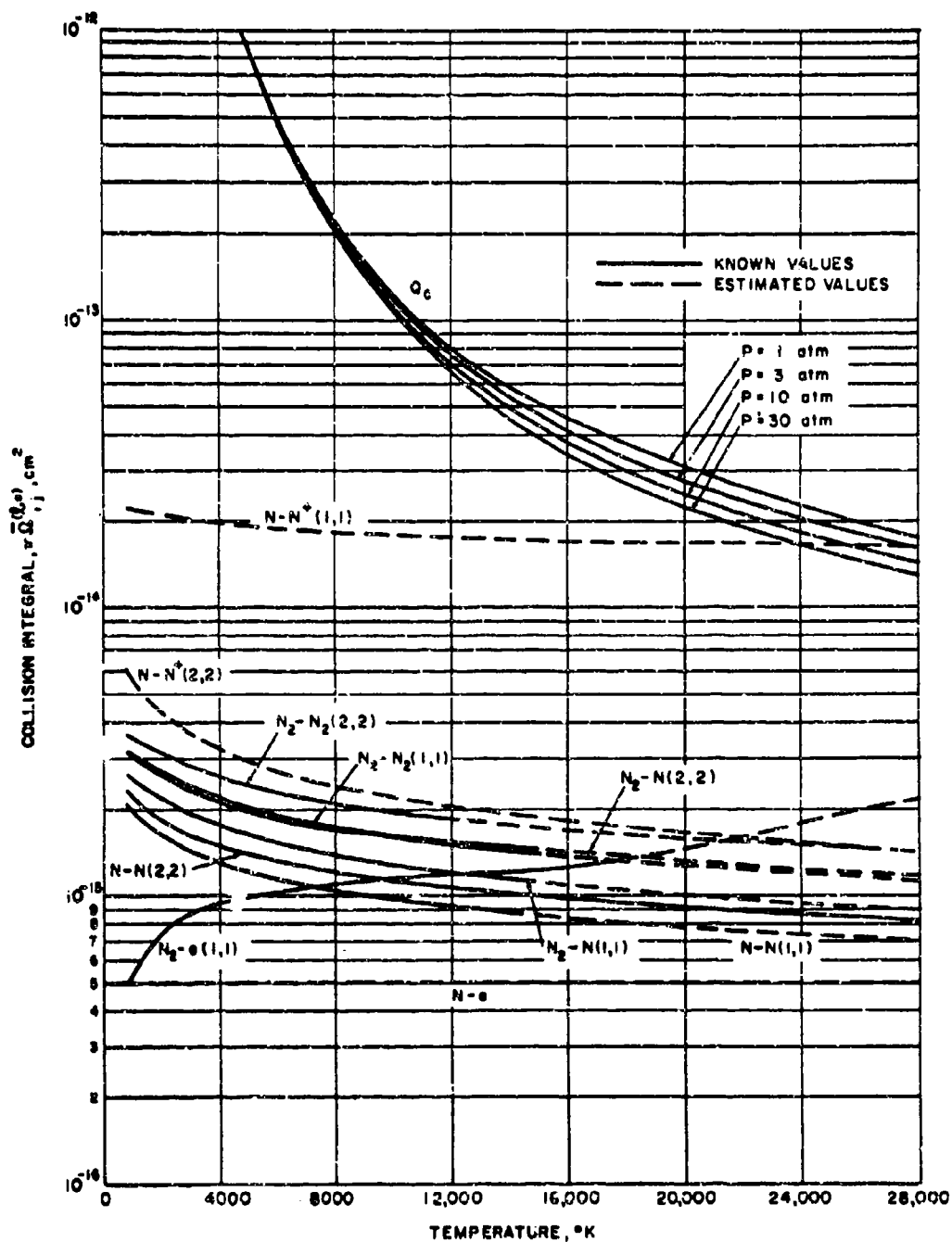


Figure 2 COLLISION INTEGRALS FOR NITROGEN VERSUS TEMPERATURE  
62-1732



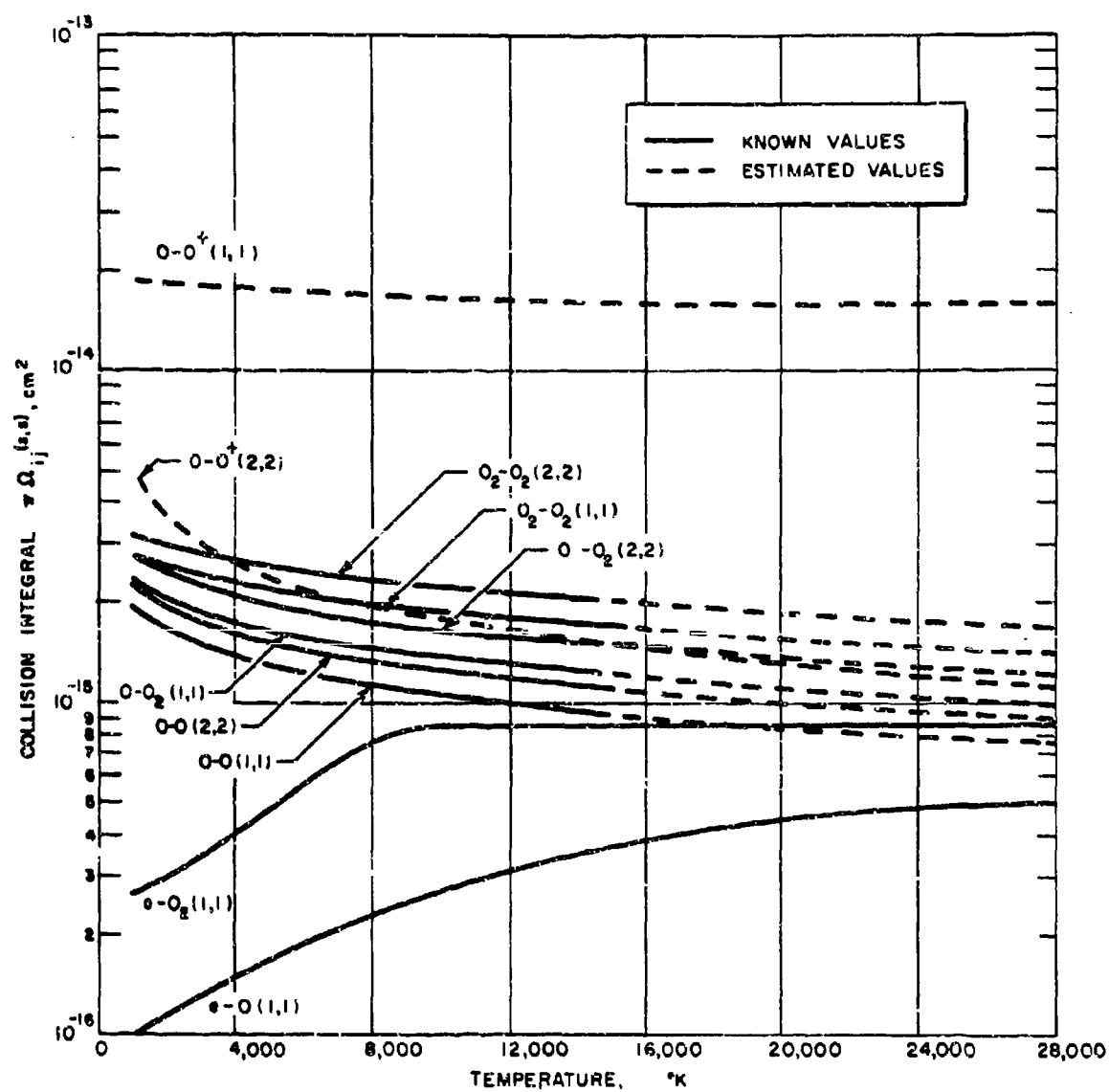


Figure 3 COLLISION INTEGRALS FOR OXYGEN VERSUS TEMPERATURE  
63-1995

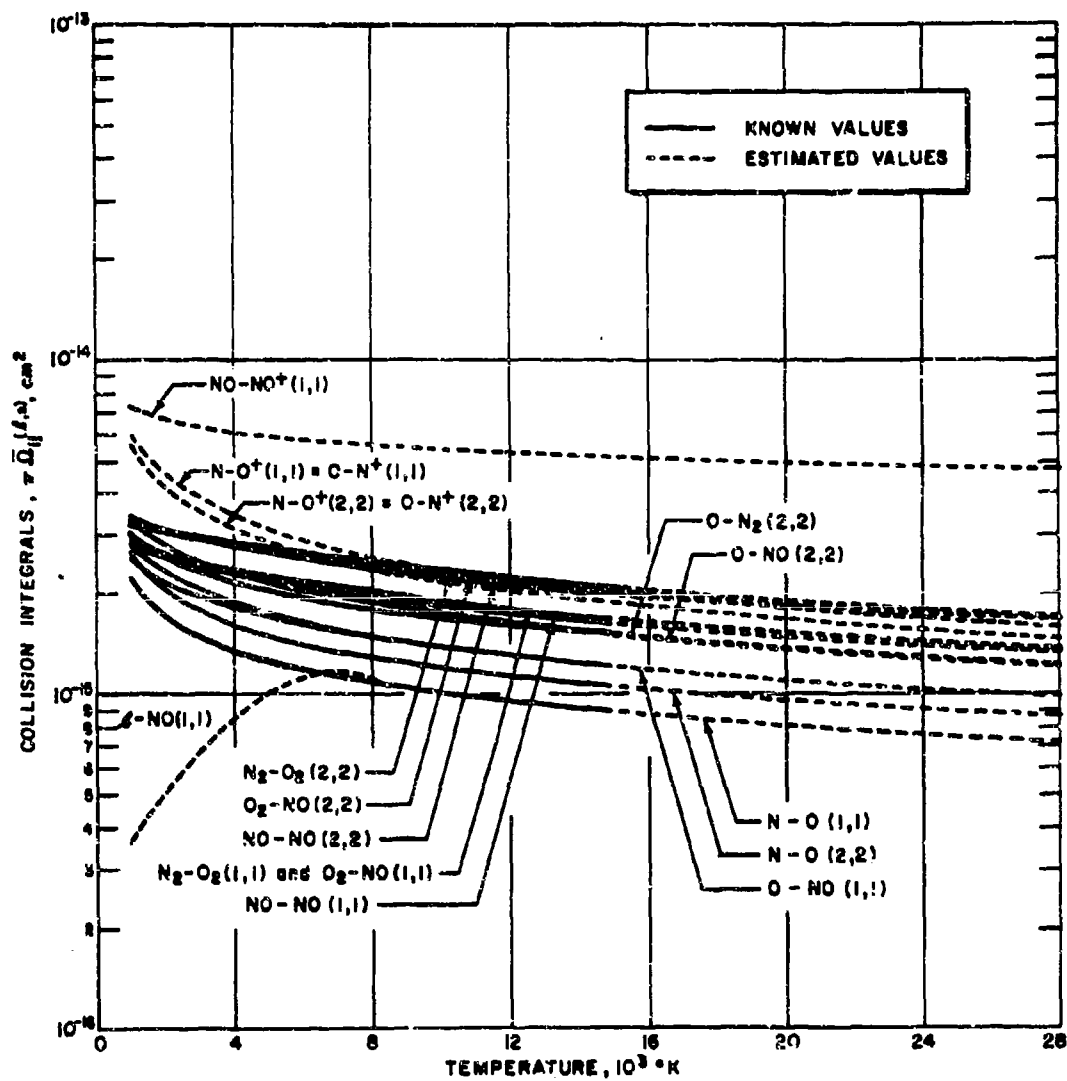


Figure 4 ADDITIONAL COLLISION INTEGRALS FOR AIR  
VERSUS TEMPERATURE  
63-1996

input data on the collision integrals, a brief discussion of the values used in the present work is given below.

The collision cross sections  $\pi \bar{\Omega}_{ij}^{(l,s)}$  for the atomic and molecular interactions (H-H, H-H<sub>2</sub>, H<sub>2</sub>-H<sub>2</sub>, N-N, N-N<sub>2</sub>, and so forth), were obtained from the recent calculations of Mason, et al.<sup>6,7</sup> for temperatures up to 15,000°K. The values for the H-H, H-H<sub>2</sub>, H<sub>2</sub>-H<sub>2</sub>, N-N, N-N<sub>2</sub>, N<sub>2</sub>-N<sub>2</sub>, O-O, O-O<sub>2</sub>, O<sub>2</sub>-O<sub>2</sub>, N-O, N<sub>2</sub>-O, and N<sub>2</sub>-O<sub>2</sub> interactions were taken directly from Mason's tabulation, while the values for O-NO, O<sub>2</sub>-NO, N<sub>2</sub>-NO, and NO-NO were calculated as averages of the above interactions, as recommended by Mason.<sup>7</sup> The cross sections for the remaining interactions N-O<sub>2</sub> and N-NO which are not tabulated by Mason were assumed to be approximately the same as for the other neutral-neutral interactions. Since these two interactions occur only very infrequently in equilibrium air, the exact values assumed for their cross sections will have a negligible effect on the calculated transport properties.

For temperatures above 15,000°K, the cross sections for the atomic interactions H-H and N-N were obtained by extending Mason's calculations up to 30,000°K, using the same potential functions as were used in his work.<sup>47,48</sup> The cross sections for the remaining neutral-neutral interactions were simply extrapolated roughly to 30,000°K, assuming the same temperature dependence as was calculated for H-H and N-N. This procedure will evidently lead to a slight error in the neutral-neutral cross sections and the corresponding binary diffusion coefficients at the highest temperatures calculated; however, since neutral species are not important at the high temperatures, the effect on the overall transport properties should be negligible.

In the case of the interactions H-H<sup>+</sup>, N-N<sup>+</sup>, O-O<sup>+</sup>, and NO-NO<sup>+</sup> between a neutral species and its own ion, it is necessary to consider the effects of resonant charge exchange. This problem is discussed in reference 49, where it is shown that charge exchange results in an anomalously large diffusion cross section  $\pi \bar{\Omega}^{(1,1)}$  but has no effect on the viscosity cross section  $\pi \bar{\Omega}^{(2,2)}$ ; the explicit formulas used in calculating these cross sections are given in reference 49. For H-H<sup>+</sup> the collision integral  $\pi \bar{\Omega}_{H-H^+}^{(2,2)}$  was obtained by approxi-

imating the H-H<sup>+</sup> interaction potentials given by Fallon, et al.<sup>47</sup> with potentials for which the collision integrals are known, just as was done above for the atomic and molecular interactions. To obtain the collision integral  $\pi \bar{\Omega}_{H-H^+}^{(1,1)}$ , the charge exchange cross section for H-H<sup>+</sup> given by Gurnee and Magee<sup>50</sup> was fitted to the analytic expression

$$Q_{ex} = (A - B \log v)^2 \quad (12)$$

with the constants  $A = 2.1 \times 10^{-7}$  cm and  $B = 2.2 \times 10^{-8}$  cm, and the expression for  $\pi \bar{\Omega}^{(1,1)}$  given in reference 49 was then integrated analytically<sup>51</sup> to obtain the result

$$\pi \bar{\Omega}_{H-H^+}^{(1,1)} = (39.8 B^2 - 17.8 AB + 2 A^2) + (8.92 B^2 - 2 AB) \left( \log \frac{T}{M} \right) + \frac{1}{2} B^2 \left( \log \frac{T}{M} \right)^2, \quad (13)$$

where the atomic weight  $M = 1.008$  for hydrogen.

There appears to be very little data available at present on the ion-neutral interactions for the nitrogen and oxygen species of interest here. Lacking any better information, the viscosity cross sections  $\pi \bar{\Omega}_{N-N^+}^{(2,2)}$  and  $\pi \bar{\Omega}_{O-O^+}^{(2,2)}$  were calculated from the approximate potentials given by Peng and Pindroh,<sup>25</sup> which they obtained by drawing a smooth curve joining the polarization potential at large internuclear distances to a Morse potential obtained from spectroscopic data at short distances. The charge exchange cross section for both oxygen and nitrogen was assumed to be of the form (12), with the constants  $A$  and  $B$  estimated in the case of oxygen by curvefitting Dalgarno's estimated cross section,<sup>52</sup> and in the case of nitrogen by means of an approximate one-electron calculation<sup>50, 53</sup> using the Hartree-Fock wave functions for nitrogen.<sup>54</sup> The values of  $A$  and  $B$  obtained in this way were  $A = 1.6 \times 10^{-7}$  cm,  $B = 1.2 \times 10^{-8}$  cm for oxygen, and  $A = 2.2 \times 10^{-7}$  cm,  $B = 2.1 \times 10^{-8}$  cm for nitrogen, with an estimated error of perhaps a factor of 2 either way in the cross sections. The charge exchange cross section for  $NO-NO^+$  was also assumed to be of the form of equation (12) with the constants  $A = 1.5 \times 10^{-7}$  cm,  $B = 1.7 \times 10^{-8}$  cm obtained by fitting experimental data in the neighborhood of 150 ev.<sup>55</sup>

For the temperatures considered in the present work, the charge-exchange cross sections for nonresonant ion-neutral collisions ( $N-O^+$ ,  $C-N^+$ ,  $N_2-N^+$ , and so forth) should be negligible, so that the collision cross sections  $\pi \bar{\Omega}^{(1,1)}$  and  $\pi \bar{\Omega}^{(2,2)}$  for such collisions will have their usual gas-kinetic values. For the case of  $N-O^+$  and  $O-N^+$ , these cross sections were again calculated from the approximate polarization potentials given by Peng and Pindroh,<sup>25</sup> and the  $N-O^+$  potential was also used to calculate the cross section  $\pi \bar{\Omega}^{(2,2)}$  for the infrequent  $NO-NO^+$  collision. The remaining ion-neutral collisions, which involve either doubly charged ions or molecules, or both, occur only very rarely for equilibrium conditions; hence, it was sufficient for the present work to take their cross sections equal to the corresponding gas kinetic values for the collisions of atoms and singly charged ions.

There has been a good deal of experimental work on the electron-molecule cross sections  $e-H_2$ ,  $e-N_2$ ,  $e-O_2$ , and  $e-NO$ , and the approximate values and general trends with electron energy seem to be well established,<sup>56-60</sup> although there is still some disagreement on the  $e-N_2$  and  $e-O_2$  cross sections at low

temperatures, 60-61 From the scatter in the results of the various experiments, we estimate an uncertainty of about 30 to 40 percent in the electron-molecule cross sections for the energies considered here. In the present work, the cross sections tabulated by Massey and Burhop<sup>56</sup> were used for e-O<sub>2</sub> and e-NO, and the values of Crompton and Sutton<sup>57</sup> were used for e-N<sub>2</sub> and e-H<sub>2</sub>. The experimental data gave the values of  $\pi\bar{\Omega}^{(1,1)}$  directly; for simplicity,  $\pi\bar{\Omega}^{(2,2)}$  was taken equal to  $\pi\bar{\Omega}^{(1,1)}$  since this approximation has a negligible effect on the calculated transport properties.

The low-energy elastic-scattering cross section for the e-H system has been studied quite extensively in the last few years,<sup>34, 62</sup> both experimentally and theoretically, and now seems to be quite well understood. In calculating the collision integrals from this data, S-wave scattering was assumed and the total cross section was approximated by means of the simple analytic curvefit

$$\sigma = \frac{5.28 \times 10^{-15}}{\sqrt{1 + (T_e/T_0)}} \text{ cm}^2 \quad (14)$$

where  $kT_e$  is the electron energy, and  $T_0 = 3300^\circ\text{K}$  is a constant. The integrals could then be evaluated analytically to give

$$\pi\bar{\Omega}_{H-e}^{(1,1)} = 5.28 \times 10^{-15} \left\{ \left[ -\frac{1}{2} \left( \frac{T_0}{T} \right)^2 + \frac{3}{4} \left( \frac{T_0}{T} \right) \right] + \left[ \left( \frac{T_0}{T} \right)^2 - \left( \frac{T_0}{T} \right) + \frac{3}{4} \right] \sqrt{\frac{T_0}{T}} \exp\left(\frac{T_0}{T}\right) \sqrt{\frac{\pi}{2}} \operatorname{erfc}\left(\sqrt{\frac{T_0}{T}}\right) \right\} \text{ cm}^2 \quad (15a)$$

$$\pi\bar{\Omega}_{H-e}^{(2,2)} = 1.76 \times 10^{-15} \left\{ \left[ \frac{1}{2} \left( \frac{T_0}{T} \right)^3 - \left( \frac{T_0}{T} \right)^2 + \frac{15}{8} \left( \frac{T_0}{T} \right) \right] + \left[ -\left( \frac{T_0}{T} \right)^3 + \frac{3}{2} \left( \frac{T_0}{T} \right)^2 - \frac{9}{4} \left( \frac{T_0}{T} \right) + \frac{15}{8} \right] \sqrt{\frac{T_0}{T}} \exp\left(\frac{T_0}{T}\right) \sqrt{\frac{\pi}{2}} \operatorname{erfc}\left(\sqrt{\frac{T_0}{T}}\right) \right\} \text{ cm}^2 \quad (15b)$$

where  $\operatorname{erfc}\left(\sqrt{\frac{T_0}{T}}\right)$  is the complimentary error function of  $\sqrt{\frac{T_0}{T}}$ .

In contrast to the case of e-H, the cross sections for e-N and e-O scattering are still quite uncertain, although some information on the e-O system is now beginning to become available.<sup>63</sup> The e-O cross sections used in the present work were obtained from a rough curvefit to the experimental data,<sup>63-64</sup> the same values being used for the diffusion and viscosity cross sections  $\pi\bar{\Omega}^{(1,1)}$  and  $\pi\bar{\Omega}^{(2,2)}$ . Following a suggestion of Kivel,<sup>65</sup> the N-e cross section was estimated by extrapolation of the experimental results on e-O, using the scaling between N and O suggested in references 66 and 67. In this way a cross section  $\pi\bar{\Omega}_{N-e}^{(1,1)} = \pi\bar{\Omega}_{N-e}^{(2,2)} = 5 \times 10^{-16} \text{ cm}^2$  is estimated, in agreement with an approximate experimental value obtained by Maecker in the electric arc.<sup>68</sup>

For the Coulomb collisions (e-e, e-H<sup>+</sup>, H<sup>+</sup>-H<sup>+</sup>, e-N<sup>+</sup>, e-N<sup>++</sup>, and so forth) effective collision integrals were chosen so as to make the calculated values of the electrical conductivity and the electronic contribution to the thermal conductivity agree as closely as possible with the results of Spitzer and Härm<sup>3</sup> when the gas is completely ionized. The value of thermal conductivity used in this comparison was Spitzer and Härm's corrected value  $\kappa_K$ , which includes the effects of ambipolar diffusion. Since Spitzer and Härm consider only the electronic contribution to the transport properties, their results do not directly determine the ion-ion collision integrals; hence it was necessary to estimate these latter quantities by comparison with the corresponding electron-ion cross sections. Thus, those transport properties, such as viscosity and reaction thermal conductivity, which depend primarily on ion-ion interactions, will probably not be given as accurately by the present calculations as are the electrical conductivity and electronic thermal conductivity which are based directly on the calculations of Spitzer and Härm. Specifically, the formulas used for the Coulomb collision integrals in our calculations were

$$\begin{array}{ll} \pi\bar{\Omega}_{e-e}^{(2,2)} = 0.75 Q_c & \pi\bar{\Omega}_{e-e}^{(1,1)} = 0.80 Q_c \\ \pi\bar{\Omega}_{e-1}^{(2,2)} = 0.75 Q_c & \pi\bar{\Omega}_{e-1}^{(1,1)} = 0.80 Q_c \\ \pi\bar{\Omega}_{e-2}^{(2,2)} = 2.1 Q_c & \pi\bar{\Omega}_{e-2}^{(1,1)} = 2.7 Q_c \\ \pi\bar{\Omega}_{1-1}^{(2,2)} = 0.30 Q_c & \pi\bar{\Omega}_{1-1}^{(1,1)} = 0.80 Q_c \\ \pi\bar{\Omega}_{1-2}^{(2,2)} = 0.84 Q_c & \pi\bar{\Omega}_{1-2}^{(1,1)} = 2.7 Q_c \end{array}$$

$$\pi \bar{n}_{2-2}^{(2,2)} = 4.8 Q_c$$

$$\pi \bar{n}_{2-2}^{(1,1)} = 12.8 Q_c$$

where the subscripts 1 and 2 indicate singly and doubly charged ions, respectively, and

$$Q_c = (e^2/kT)^2 \ln \Lambda = 3.22 \times 10^{-6} \frac{\log_{10} \Lambda^2}{T^2} \text{ cm}^2 \quad (16b)$$

is the well known Gvosdover cross section for Coulomb collisions. In evaluating the cutoff parameter  $\Lambda$  in equation (16b), a cutoff at the Debye length for low electron densities and at the mean ionic distance for high electron densities has been used, as recommended by Spitzer and Härm,<sup>3</sup> and interpolated between the two extreme cases by means of a root-mean-square interpolation formula,

$$\Lambda^2 = \frac{9(kT)^3}{4\pi e^6 n_e} + \frac{16(kT)^2}{e^4 n_e^{2/3}} \quad (16c)$$

where  $n_e$  is the number of free electrons per unit volume.

The nitrogen and oxygen atoms have low-lying electronic states at a few electron volts which are appreciably populated for the conditions of the calculations. To estimate the effect of these states on the transport properties, it is noted that they belong to the same electronic configuration as the ground state, and hence have approximately the same radii for the electronic charge distribution. It is therefore expected that the collision cross sections for these excited atoms will be roughly the same as they are for ground-state atoms, except for cases in which exchange of excitation energy can occur, and that the cross section for the latter process will be of the same order as the corresponding charge exchange cross section.<sup>49</sup> Thus, it is expected that the only important effect of the low-lying excited states will be to reduce the contribution to the internal thermal conductivity due to excited nitrogen and oxygen atoms by impeding the relative diffusion of the ground-state and excited atoms. This effect has been taken into account in the transport property calculations by replacing the collision integrals  $\pi \bar{n}_{N-N}^{(1,1)}$  and  $\pi \bar{n}_{O-O}^{(1,1)}$  in equation (5) for  $K_{int}$  by the corresponding values  $\pi \bar{n}_{N-N^+}^{(1,1)}$  and  $\pi \bar{n}_{O-O^+}^{(1,1)}$  estimated for charge exchange. With this approximation, the calculated value of  $K_{int}$  due to excited atoms is very small, so that the final transport-property values are essentially the same as would have been obtained if the effects of excited electronic states had been neglected altogether.

The low-lying excited states of ionized nitrogen and oxygen will behave similarly to those of the un-ionized atoms, except that in this case the Coulomb cross sections should dominate the cross section for excitation exchange, so that there will be no effect at all on the transport properties, and equations (2) through (10) will be correct as they stand.

The above arguments do not apply to highly excited electronic states since these have considerably larger radii than the ground states, and hence much larger collision cross sections; however, the number of atoms in these highly excited states is low enough for the conditions of this work that they are not expected to have a major effect on the transport properties.

In calculating the total radiated power in the continuum from equation (11) the effective charge  $Z_{\text{eff}}$  for the ions was taken to be equal to their actual net charge, while for the neutrals the approximate value  $Z_{\text{eff}}^2 = 0.02/3$  suggested by Kivel and Bailey<sup>69</sup> for nitrogen was used in all cases. While this approximation is of course not too accurate in detail, we believe that it should reflect the main features of the total radiation rather well at the higher temperatures (above about 10,000°K).



### III. RESULTS OF TRANSPORT AND RADIATION PROPERTY CALCULATIONS

The final results of the transport and radiation property calculations are given in tables I through XVIII, and figures 7 through 22.\* For the lower temperatures where ionization is not important, the overall accuracy of the calculated transport properties (except diffusion coefficients and radiation) is estimated to be about 10 to 20 percent, this error being due primarily to uncertainties in the knowledge of the required collision cross sections. At the higher temperatures, the accuracy of the calculated transport properties becomes considerably poorer; for hydrogen, a probable error of about 50 percent is estimated, due primarily to the approximate treatment of Coulomb collisions and of excited states in the calculation; for the other gases, the probable error is somewhat greater because of lack of knowledge of the ion-atom and electron-atom interactions.

For convenience in the applications, binary diffusion coefficients have been tabulated for all molecular pairs for which cross sections are given in figures 1 through 4, even though in some cases the relevant collision cross sections are not known too accurately. Those pairs for which the diffusion coefficients are felt to be significantly less accurate than the transport properties for the gas as a whole are indicated by an asterisk in the tables. In all cases however, it is believed that the tabulated diffusion coefficients should be within at least a factor of 2 or 3 of the correct value. For an ionized gas, the usual quantity of interest in the applications is the ambipolar diffusion coefficient, which is equal to approximately twice the ion-neutral coefficient tabulated here.

The calculated values of the continuum radiated power are estimated to be correct within a factor of 2 or 3.

Transport properties have been calculated recently for un-ionized hydrogen, nitrogen, oxygen, and air up to about 10,000°K by Mason, et al,<sup>5-7</sup> using the same input data on the neutral-neutral collision cross sections as were used in the present work. As would be expected, our results are in essential agreement with those of Mason, et al, for the lower temperatures; however, for temperatures of about 7000°K and above the effects of ionization are no longer negligible, and our calculations begin to deviate significantly from Mason's values.

At the highest temperatures considered, our values for the electrical and thermal conductivity are in good agreement with the results of Spitzer, et al<sup>3</sup> for a fully ionized gas, as they should be. For the intermediate temperature range,

\*Approximate values of the thermodynamic properties for the conditions covered in this report can be found in reference 43.

from about 10,000 to 20,000°K, however, the present results appear to differ rather significantly from those obtained by earlier investigators, due primarily to differences in the assumed collision cross sections. In particular, the explicit inclusion of charge-exchange effects in the present work results in a diffusion cross section  $\sigma_{(1,1)}$  between atoms and atomic-ions which is almost an order of magnitude larger than the gas-kinetic cross section used in most previous high-temperature transport-property calculations. This leads to a reduction of almost an order of magnitude in the reaction thermal conductivity due to ionization, so that it becomes comparable to the translational thermal conductivity; hence, the large peak in the total thermal conductivity in the ionization region, which was obtained in many of the previous calculations, no longer occurs. Since the specific heat is still strongly peaked, the equilibrium Prandtl number  $N_{Pr} = \mu c_p / K$  now exhibits a sizeable peak in the ionization region, before falling off to the low value characteristic of a fully ionized gas. This behavior is illustrated in figure 5 for air; the values of  $\mu$  and  $K$  used in calculating this figure were obtained from the present report, and the value of  $c_p$  from reference 43.

Figure 6 compares the total thermal conductivity for nitrogen calculated in the present report with some experimental measurements obtained by Maecker<sup>68</sup> in the electric arc. Maecker's results are seen to agree very well with the calculations at the lower temperatures; however at about the temperature at which significant ionization begins to occur, the experimental thermal conductivity curve starts to rise rapidly above the calculated value, and, at the highest temperatures observed, it is about an order of magnitude higher than the calculations. Maecker attributes this rapid rise to the reaction thermal conductivity of ionization. As we have pointed out above however, the reaction conductivity could not have such a high value unless the resonant charge exchange cross section for  $N-N^+$  were almost an order of magnitude less than estimated here (see figure 2). Although this cross section is not known accurately at present, it seems very unlikely, on theoretical grounds, that it could be as low as would be required to account for Maecker's experimental data. We therefore feel that the discrepancy between Maecker's data and the theoretical calculations must still be regarded as unexplained.

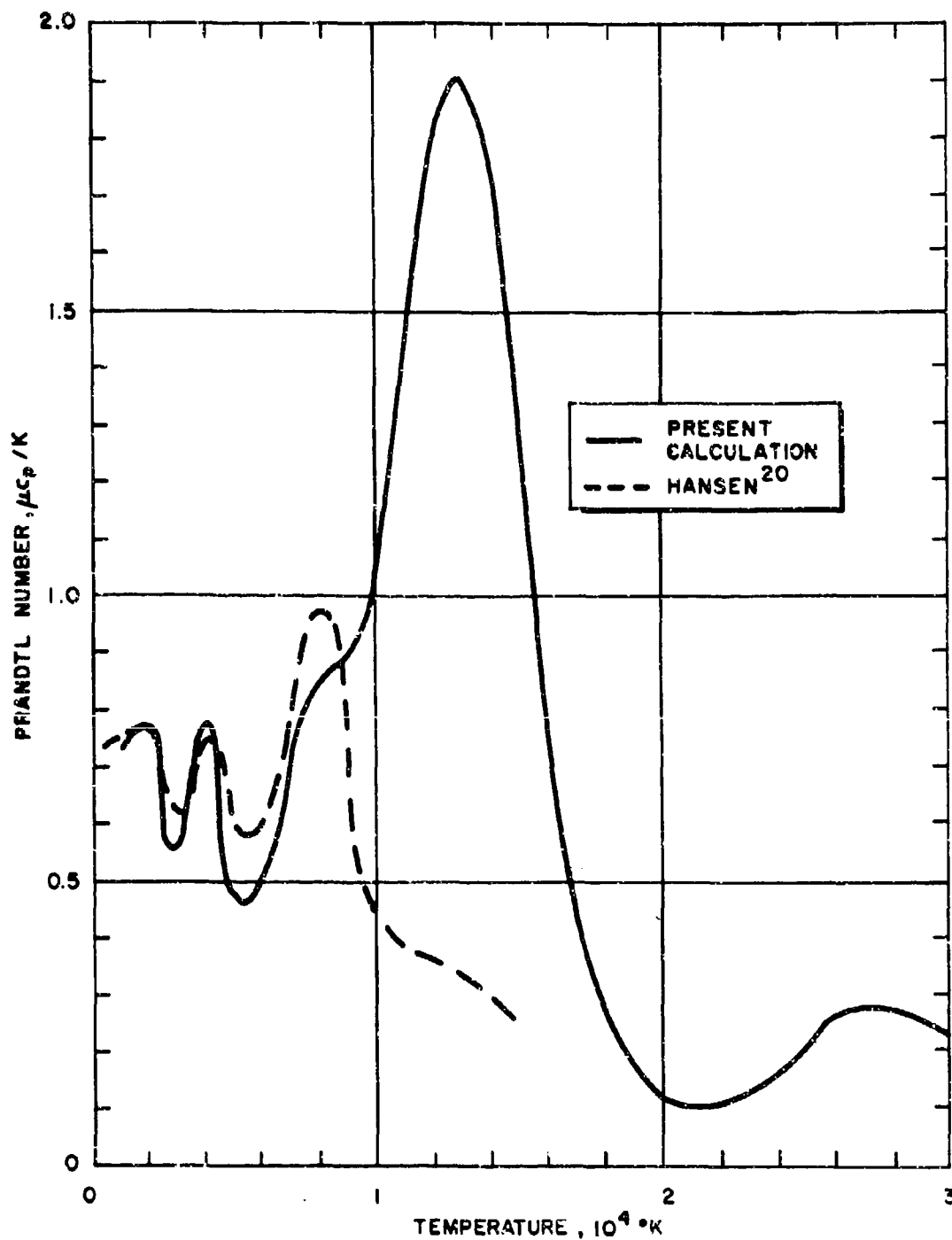


Figure 5 PRANDTL NUMBER FOR EQUILIBRIUM AIR AT ATMOSPHERIC  
PRESSURE VERSUS TEMPERATURE  
63-1997

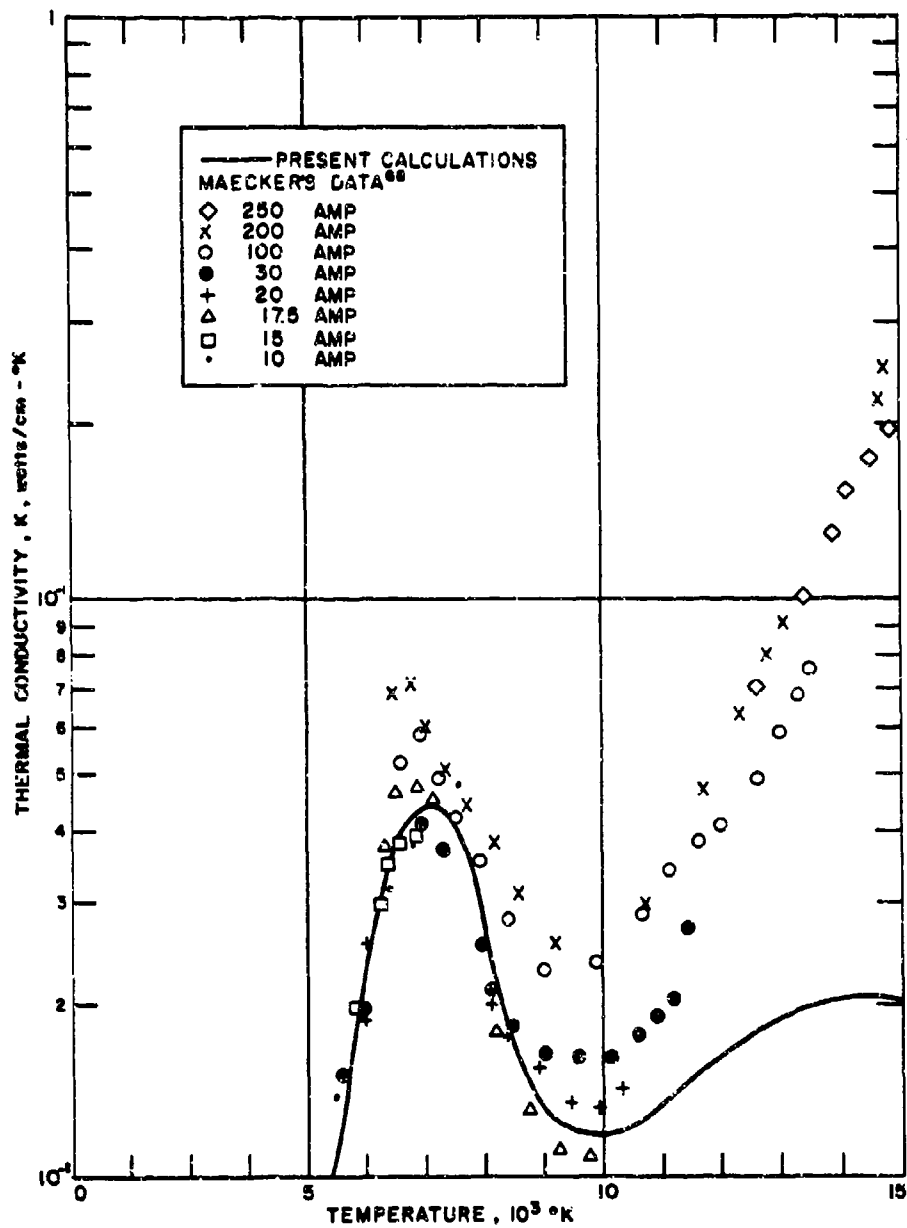


Figure 6 THERMAL CONDUCTIVITY OF NITROGEN AT ATMOSPHERIC PRESSURE -- COMPARISON WITH EXPERIMENT  
63-1998

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TABLE I

VISCOSITY OF EQUILIBRIUM HYDROGEN  
(in millipoise)

Temperature (°K;	Pressure (atm)			
	1	3	10	30
1,000	0.199	0.199	0.199	0.199
2,000	0.319	0.319	0.319	0.319
3,000	0.448	0.445	0.442	0.440
4,000	0.533	0.567	0.581	0.579
5,000	0.555	0.577	0.623	0.672
6,000	0.636	0.641	0.658	0.694
7,000	0.732	0.734	0.740	0.755
8,000	0.827	0.830	0.833	0.841
9,000	0.914	0.922	0.927	0.933
10,000	0.975	0.999	1.01	1.02
12,000	0.937	1.05	1.12	1.17
14,000	0.661	0.889	1.09	1.21
16,000	0.357	0.593	0.877	1.10
18,000	0.205	0.358	0.618	0.899
20,000	0.161	0.248	0.431	0.686
22,000	0.161	0.214	0.332	0.527
24,000	0.178	0.215	0.301	0.447
26,000	0.205	0.238	0.304	0.418
28,000	0.237	0.268	0.326	0.420
30,000	0.272	0.305	0.360	0.444

TABLE II

FROZEN THERMAL CONDUCTIVITY

$K_f = K_{tr} + K_{int}$  FOR HYDROGEN  
(in mw/cm - °K)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	4.37	4.37	4.37	4.37
2,000	8.06	8.06	8.05	8.05
3,000	12.6	12.4	12.3	12.2
4,000	15.9	16.8	17.2	17.1
5,000	17.1	17.7	18.9	20.4
6,000	19.6	19.8	20.2	21.1
7,000	22.7	22.7	22.9	23.2
8,000	26.0	25.9	25.9	26.0
9,000	29.5	29.4	29.3	29.2
10,000	32.6	32.9	32.9	32.8
12,000	33.9	37.3	39.4	40.1
14,000	28.4	35.8	42.1	45.8
16,000	22.7	30.7	40.1	47.4
18,000	22.2	28.1	37.3	46.9
20,000	25.1	29.6	37.3	46.8
22,000	29.9	33.8	40.3	48.8
24,000	35.6	39.4	45.7	54.1
26,000	42.2	46.6	53.0	61.0
28,000	49.6	54.4	61.3	69.2
30,000	57.4	63.0	70.9	79.4

TABLE III  
EQUILIBRIUM THERMAL CONDUCTIVITY  
 $K = K_t + K_r$  FOR HYDROGEN  
(in mw/cm - °K)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	4.37	4.37	4.37	4.37
2,000	9.03	8.62	8.37	8.23
3,000	69.0	46.2	31.2	23.3
4,000	148	155	123	87.7
5,000	36.3	64.9	111	133
6,000	22.4	27.8	44.0	74.3
7,000	23.6	24.8	29.0	40.0
8,000	27.1	27.1	28.2	32.2
9,000	32.2	31.2	31.0	32.2
10,000	40.0	37.2	35.7	35.5
12,000	59.0	53.1	48.8	46.1
14,000	75.8	71.1	65.1	60.9
16,000	64.8	76.7	78.3	75.4
18,000	42.3	62.0	78.7	84.8
20,000	33.0	47.0	68.1	84.4
22,000	33.2	41.9	58.5	77.8
24,000	37.1	43.4	56.0	77.7
26,000	43.0	48.8	59.0	75.8
28,000	50.0	55.7	64.9	77.6
30,000	57.7	63.8	73.3	85.2

**TABLE IV**  
**ELECTRICAL CONDUCTIVITY OF EQUILIBRIUM HYDROGEN**  
(in mhos/cm)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	---	---	---	---
2,000	$1.83 \times 10^{-14}$	$8.08 \times 10^{-15}$	$3.31 \times 10^{-15}$	$1.47 \times 10^{-15}$
3,000	$9.67 \times 10^{-8}$	$4.55 \times 10^{-8}$	$1.92 \times 10^{-8}$	$8.64 \times 10^{-9}$
4,000	$1.38 \times 10^{-4}$	$7.56 \times 10^{-5}$	$3.70 \times 10^{-5}$	$1.82 \times 10^{-5}$
5,000	$6.66 \times 10^{-3}$	$3.81 \times 10^{-3}$	$2.05 \times 10^{-3}$	$1.12 \times 10^{-3}$
6,000	0.111	$6.40 \times 10^{-2}$	$3.48 \times 10^{-2}$	$1.99 \times 10^{-2}$
7,000	0.840	0.497	0.275	0.160
8,000	3.47	2.17	1.25	0.738
9,000	9.29	6.39	3.96	2.43
10,000	18.6	14.7	10.4	7.11
12,000	37.0	34.5	29.7	24.1
14,000	53.5	54.0	52.1	47.9
16,000	67.2	71.0	73.4	72.1
18,000	79.4	86.0	91.4	94.9
20,000	90.2	98.6	108	115
22,000	101	111	122	132
24,000	112	122	136	150
26,000	123	135	149	164
28,000	135	147	163	180
30,000	145	160	177	195

TABLE V

BINARY DIFFUSION COEFFICIENTS FOR HYDROGEN  
AT ATMOSPHERIC PRESSURE

Temperature °K	Binary Diffusion Coefficient, $D_{ij}$ ( $\text{cm}^2/\text{sec}$ )				
	(H, H <sub>2</sub> )	(H, H <sup>+</sup> )	(H <sub>2</sub> , H <sup>+</sup> )*	(e, H <sub>2</sub> )	(e, H)
1,000	17.2	2.08	2.68	680	189
2,000	61.8	6.45	11.5	1650	676
3,000	133	12.4	26.7	2810	1410
4,000	230	19.8	48.7	4090	2390
5,000	354	28.5	77.7	5510	3630
6,000	505	38.6	115	7060	5060
7,000	684	49.6	157	8740	6820
8,000	889	61.8	207	10600	8830
9,000	1130	74.9	267	12500	11000
10,000	1390	89.0	334	14700	13500
12,000	2010	120	480	19500	19300
14,000	2760	155	682	25300	26000
16,000	3620	193	924	31900	33600
18,000	4650	234	1210	39600	42400
20,000	5810	278	1550	48300	51800
22,000	7090	325	1920	57300	62600
24,000	8570	376	2340	66200	74200
26,000	10200	429	2820	74600	87100
28,000	11900	484	3360	83400	101000
30,000	13900	543	3950	92500	116000

\*Estimated interaction potential

TABLE VI  
 VISCOSITY OF EQUILIBRIUM NITROGEN  
 (in millipoise)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	0.400	0.40	0.400	0.400
2,000	0.631	0.631	0.631	0.631
3,000	0.853	0.853	0.853	0.853
4,000	1.07	1.07	1.07	1.07
5,000	1.28	1.28	1.28	1.28
6,000	1.51	1.50	1.49	1.48
7,000	1.82	1.76	1.72	1.70
8,000	2.20	2.12	2.02	1.96
9,000	2.46	2.45	2.38	2.28
10,000	2.62	2.66	2.66	2.61
12,000	2.51	2.76	2.94	3.02
14,000	1.70	2.26	2.77	3.07
16,000	0.88	1.43	2.15	2.70
18,000	0.56	0.88	1.47	2.10
20,000	0.51	0.69	1.06	1.58
22,000	0.56	0.68	0.92	1.28
24,000	0.60	0.73	0.92	1.19
26,000	0.56	0.76	0.97	1.21
28,000	0.44	0.70	1.01	1.27
30,000	0.30	0.57	0.95	1.30

TABLE VII

FROZEN THERMAL CONDUCTIVITY  $k_f = k_{tr} + k_{int}$   
FOR NITROGEN  
(in mw/cm-°K)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	0.671	0.671	0.671	0.671
2,000	1.17	1.17	1.17	1.17
3,000	1.63	1.63	1.63	1.63
4,000	2.09	2.09	2.09	2.09
5,000	2.55	2.54	2.54	2.54
6,000	3.14	3.07	3.03	3.00
7,000	4.22	3.90	3.69	3.58
8,000	5.99	5.47	4.86	4.46
9,000	7.70	7.41	6.80	6.04
10,000	9.25	9.22	8.92	8.29
12,000	11.7	12.5	13.0	13.2
14,000	13.1	15.0	16.7	17.9
16,000	14.7	17.1	20.0	22.2
18,000	17.8	20.3	23.6	26.7
20,000	21.7	24.5	28.0	31.9
22,000	26.8	29.6	33.4	37.8
24,000	31.5	35.3	39.7	44.9
26,000	36.2	40.9	46.7	52.5
28,000	39.6	46.1	53.5	61.0
30,000	43.7	50.5	59.9	68.8



TABLE VIII

EQUILIBRIUM THERMAL CONDUCTIVITY  $k = k_f + k_r$   
FOR NITROGEN  
(in mw/cm-°K)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	0.671	0.671	0.671	0.671
2,000	1.17	1.17	1.17	1.17
3,000	1.64	1.64	1.64	1.64
4,000	2.36	2.24	2.17	2.14
5,000	6.34	4.75	3.75	3.24
6,000	23.1	14.8	9.98	7.08
7,000	44.5	36.5	25.1	17.0
8,000	26.4	38.2	40.0	32.3
9,000	12.9	19.6	31.6	38.3
10,000	11.5	13.1	18.6	27.9
12,000	16.2	15.7	15.9	16.9
14,000	20.4	21.0	21.0	21.2
16,000	19.5	23.4	26.1	27.1
18,000	19.6	23.7	28.7	32.2
20,000	22.3	25.9	30.9	36.1
22,000	27.2	30.2	34.8	40.3
24,000	32.3	35.8	40.4	46.2
26,000	38.1	42.0	47.4	53.3
28,000	43.2	48.5	54.8	61.9
30,000	47.8	54.5	62.4	70.2

TABLE IX

ELECTRICAL CONDUCTIVITY OF EQUILIBRIUM NITROGEN  
(in mhos/cm)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	---	---	---	---
2,000	$2.29 \times 10^{-18}$	$1.00 \times 10^{-18}$	$4.07 \times 10^{-19}$	$1.79 \times 10^{-19}$
3,000	$4.25 \times 10^{-10}$	$1.86 \times 10^{-10}$	$7.56 \times 10^{-11}$	$3.32 \times 10^{-11}$
4,000	$6.34 \times 10^{-6}$	$2.78 \times 10^{-6}$	$1.13 \times 10^{-6}$	$4.95 \times 10^{-7}$
5,000	$2.14 \times 10^{-3}$	$9.34 \times 10^{-4}$	$3.78 \times 10^{-4}$	$1.66 \times 10^{-4}$
6,000	0.111	$4.55 \times 10^{-2}$	$1.91 \times 10^{-2}$	$8.34 \times 10^{-3}$
7,000	1.78	0.804	0.323	0.139
8,000	9.02	5.74	2.82	1.31
9,000	18.6	15.5	10.8	6.30
10,000	27.3	25.6	21.9	16.7
12,000	42.8	44.3	44.2	42.6
14,000	57.1	60.4	63.5	65.4
16,000	68.8	74.7	81.2	85.5
18,000	79.8	87.9	96.8	104
20,000	89.1	99.5	111	122
22,000	99.9	110	124	137
24,000	105	120	136	151
26,000	105	125	146	165
28,000	101	124	152	175
30,000	99	120	152	181

TABLE X  
 VISCOSITY OF EQUILIBRIUM OXYGEN  
 (in millipoise)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	0.482	0.482	0.482	0.482
2,000	0.732	0.732	0.732	0.732
3,000	0.949	0.944	0.940	0.938
4,000	1.27	1.23	1.20	1.17
5,000	1.54	1.54	1.52	1.48
6,000	1.78	1.78	1.78	1.77
7,000	2.01	2.01	2.01	2.01
8,000	2.23	2.23	2.23	2.23
9,000	2.44	2.45	2.45	2.46
10,000	2.62	2.64	2.66	2.66
12,000	2.74	2.90	2.99	3.04
14,000	2.27	2.76	3.10	3.28
16,000	1.40	2.11	2.80	3.24
18,000	0.82	1.36	2.16	2.87
20,000	0.65	0.95	1.56	2.31
22,000	---	0.83	1.22	1.82
24,000	0.72	0.86	1.12	1.56
26,000	0.79	0.93	1.16	1.48
28,000	0.77	1.00	1.24	1.52
30,000	0.66	0.98	1.30	1.58

TABLE XI

FROZEN THERMAL CONDUCTIVITY  $K_f = K_u + K_{int}$  FOR OXYGEN  
(in mw/cm - °K)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	0.754	0.754	0.754	0.754
2,000	1.25	1.25	1.25	1.25
3,000	1.73	1.72	1.70	1.70
4,000	2.47	2.39	2.30	2.23
5,000	3.03	3.02	2.99	2.93
6,000	3.60	3.56	3.54	3.55
7,000	4.48	4.34	4.22	4.19
8,000	5.72	5.54	5.30	5.14
9,000	7.10	6.99	6.75	6.43
10,000	8.53	8.54	8.43	8.14
12,000	11.4	12.0	12.3	12.4
14,000	13.7	15.2	16.5	17.3
16,000	15.4	17.9	20.5	22.2
18,000	18.1	20.8	24.3	27.3
20,000	21.8	24.8	28.4	32.5
22,000	---	29.6	33.6	38.2
24,000	32.1	35.5	39.8	45.0
26,000	28.1	41.9	47.1	52.6
28,000	42.8	48.9	54.7	61.2
30,000	47.2	55.3	62.9	68.9

TABLE XII

EQUILIBRIUM THERMAL CONDUCTIVITY  $k = k_f + k_r$  FOR OXYGEN  
(inmw/cm - °K)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	0.754	0.754	0.754	0.754
2,000	1.32	1.29	1.27	1.26
3,000	8.02	5.44	3.78	2.91
4,000	21.4	21.5	16.6	11.7
5,000	5.09	8.24	13.9	17.4
6,000	3.83	4.23	5.59	8.55
7,000	4.55	4.47	4.60	5.26
8,000	5.84	5.62	5.39	5.30
9,000	7.47	7.21	6.87	6.50
10,000	9.43	9.08	8.74	8.34
12,000	14.7	14.1	13.5	13.2
14,000	20.3	20.1	19.6	19.3
16,000	21.4	24.5	26.0	26.2
18,000	20.9	25.6	30.3	32.8
20,000	22.9	27.1	32.7	37.9
22,000	---	30.7	36.0	42.2
24,000	32.5	36.0	41.0	47.5
26,000	38.8	42.4	47.8	54.0
28,000	44.9	50.1	55.5	62.2
30,000	51.2	58.0	64.3	69.8

TABLE XII

ELECTRICAL CONDUCTIVITY OF EQUILIBRIUM OXYGEN  
(in mhos/cm)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	$8.0 \times 10^{-35}$	$2.4 \times 10^{-35}$	$1.24 \times 10^{-35}$	$5.43 \times 10^{-36}$
2,000	$2.6 \times 10^{-14}$	$1.3 \times 10^{-14}$	$6.07 \times 10^{-15}$	$2.66 \times 10^{-15}$
3,000	$1.9 \times 10^{-7}$	$9.2 \times 10^{-8}$	$4.81 \times 10^{-8}$	$2.10 \times 10^{-8}$
4,000	$1.0 \times 10^{-3}$	$4.1 \times 10^{-4}$	$1.55 \times 10^{-4}$	$6.36 \times 10^{-5}$
5,000	$1.1 \times 10^{-1}$	$5.2 \times 10^{-2}$	$2.02 \times 10^{-2}$	$8.93 \times 10^{-3}$
6,000	1.14	0.681	0.370	0.197
7,000	5.46	3.75	2.30	1.38
8,000	13.1	10.7	7.82	5.39
9,000	21.1	19.3	16.2	12.6
10,000	28.7	27.9	25.7	22.4
12,000	43.1	44.7	45.0	44.0
14,000	57.1	60.4	63.4	65.3
16,000	68.8	74.6	80.9	84.9
18,000	79.8	87.8	96.5	104
20,000	89.3	99.5	110	121
22,000	---	111	123	137
24,000	111	122	137	151
26,000	118	133	150	166
28,000	118	142	161	179
30,000	115	144	170	186

TABLE XIV

VISCOSITY OF EQUILIBRIUM AIR  
(in millipoise)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	0.418	0.418	0.418	0.418
2,000	0.648	0.648	0.648	0.648
3,000	0.858	0.857	0.857	0.856
4,000	1.08	1.07	1.07	1.06
5,000	1.30	1.30	1.30	1.27
6,000	1.54	1.52	1.51	1.50
7,000	1.86	1.80	1.76	1.73
8,000	2.21	2.15	2.06	2.00
9,000	2.46	2.45	2.40	2.32
10,000	2.63	2.66	2.67	2.63
12,000	2.63	2.85	3.00	3.06
14,000	1.77	2.34	2.82	3.10
16,000	0.96	1.53	2.24	----
18,000	0.60	0.96	1.57	2.21
20,000	0.54	----	1.13	1.69
22,000	0.58	0.70	0.96	1.36
24,000	0.63	0.75	0.95	1.24
26,000	0.62	0.80	1.01	1.25
28,000	0.53	0.78	1.06	1.32
30,000	0.42	0.67	1.04	1.37

TABLE XV

FROZEN THERMAL CONDUCTIVITY  $k_f = k_u + k_{int}$  FOR AIR  
(in mw/cm - °K)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	0.690	0.690	0.690	0.690
2,000	1.18	1.18	1.18	1.18
3,000	1.63	1.63	1.63	1.62
4,000	2.11	2.10	2.08	2.06
5,000	2.62	2.61	2.59	2.52
6,000	3.29	3.20	3.13	3.08
7,000	4.40	4.13	3.90	3.76
8,000	5.97	5.58	5.11	4.76
9,000	7.58	7.33	6.83	6.24
10,000	9.12	9.07	8.78	8.24
12,000	11.8	12.5	12.9	12.8
14,000	13.0	15.0	16.7	17.8
16,000	4.8	17.2	20.1	----
18,000	17.9	20.4	23.7	26.8
20,000	21.8	----	27.7	31.9
22,000	26.8	29.6	33.4	37.9
24,000	31.7	35.3	39.7	44.9
26,000	36.7	41.2	46.8	52.5
28,000	40.5	46.8	53.8	61.1
30,000	44.8	51.6	60.6	69.2



TABLE XVI

EQUILIBRIUM THERMAL CONDUCTIVITY  $k = k_f + k_r$  FOR AIR  
(in mw/cm - °K)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	0.690	0.690	0.690	0.690
2,000	1.21	1.20	1.19	1.19
3,000	3.83	2.99	2.41	2.08
4,000	5.00	5.55	5.38	4.65
5,000	8.81	7.43	6.63	6.16
6,000	21.3	15.5	11.8	9.86
7,000	35.2	31.1	23.4	17.7
8,000	19.7	29.0	32.6	28.6
9,000	11.2	15.5	24.2	30.6
10,000	11.2	12.0	15.4	21.9
12,000	16.2	15.6	15.3	15.9
14,000	20.7	21.6	21.6	21.5
16,000	20.7	24.4	27.1	----
18,000	20.8	25.2	30.3	33.7
20,000	22.9	----	32.2	37.9
22,000	27.4	30.8	36.0	42.1
24,000	32.4	36.0	41.2	47.5
26,000	38.3	42.2	47.8	54.2
28,000	43.4	48.8	55.1	62.4
30,000	48.4	54.9	62.8	70.7

TABLE XVII

ELECTRICAL CONDUCTIVITY OF EQUILIBRIUM AIR  
(in mhos/cm)

Temperature (°K)	Pressure (atm)			
	1	3	10	30
1,000	-----	-----	-----	-----
2,000	$9.98 \times 10^{-9}$	$5.75 \times 10^{-9}$	$2.77 \times 10^{-9}$	$1.81 \times 10^{-9}$
3,000	$2.14 \times 10^{-4}$	$1.51 \times 10^{-4}$	$6.71 \times 10^{-5}$	$3.78 \times 10^{-5}$
4,000	$2.43 \times 10^{-2}$	$1.55 \times 10^{-2}$	$8.90 \times 10^{-3}$	$5.12 \times 10^{-3}$
5,000	$2.94 \times 10^{-1}$	$2.10 \times 10^{-1}$	$1.43 \times 10^{-1}$	$8.28 \times 10^{-2}$
6,000	1.13	0.78	0.57	0.41
7,000	3.90	2.47	1.79	1.33
8,000	10.4	7.20	4.83	3.40
9,000	19.0	15.9	11.9	8.23
10,000	27.3	25.5	21.9	17.2
12,000	42.7	43.8	43.0	40.1
14,000	55.9	60.4	63.5	65.5
16,000	68.8	74.7	81.2	-----
18,000	79.8	87.9	96.8	104
20,000	89.2	-----	109	122
22,000	100	110	123	137
24,000	107	120	136	151
26,000	108	127	147	165
28,000	105	128	154	176
30,000	104	125	156	184

TABLE XVIII

BINARY DIFFUSION COEFFICIENTS FOR THE CONSTITUENTS OF AIR  
AT ATMOSPHERIC PRESSURE

Temperature (°K)	Binary Diffusion Coefficient $D_{ij}$ ( $\text{cm}^2/\text{sec}$ )				
	(N, N <sub>2</sub> )	(N, N <sup>+</sup> )*	(N <sub>2</sub> , N <sup>+</sup> )*	(N <sup>+</sup> , N <sup>++</sup> )	(O, O <sub>2</sub> )
1,000	2.34	0.313	1.06	$1.78 \times 10^{-5}$	2.40
2,000	7.95	0.940	3.99	$4.33 \times 10^{-4}$	7.87
3,000	16.4	1.79	8.67	$2.90 \times 10^{-3}$	15.9
4,000	27.5	2.83	15.1	$1.06 \times 10^{-2}$	26.2
5,000	41.2	4.04	23.1	$2.99 \times 10^{-2}$	37.6
6,000	57.4	5.40	32.8	$6.88 \times 10^{-2}$	53.1
7,000	76.0	6.91	43.9	0.138	69.7
8,000	97.2	8.53	56.7	0.245	88.2
9,000	121	10.3	71.2	0.399	109
10,000	147	12.2	86.8	0.604	131
12,000	206	16.3	123	1.23	181
14,000	274	20.8	166	2.16	238
16,000	354	25.8	214	3.38	304
18,000	439	31.2	268	4.93	376
20,000	533	36.7	328	6.85	457
22,000	637	42.9	395	9.40	544
24,000	749	49.1	464	12.3	639
26,000	869	56.1	541	16.1	740
28,000	998	63.0	626	20.4	849
30,000	1130	70.3	714	25.5	966

\*Estimated Interaction Potential

TABLE XVIII (Cont'd)

BINARY DIFFUSION COEFFICIENTS FOR THE CONSTITUENTS OF AIR  
AT ATMOSPHERIC PRESSURE

Temperature (°K)	Binary Diffusion Coefficient, $D_{ij}$ ( $\text{cm}^2/\text{sec}$ )				
	(O, O <sup>+</sup> )*	(N <sub>2</sub> , O <sub>2</sub> )	(N <sub>2</sub> , O)	(N, O)	(N, O <sup>+</sup> )* and (O, N <sup>+</sup> )*
1,000	0.347	1.64	2.08	3.01	1.13
2,000	1.02	5.14	7.07	11.0	4.22
3,000	1.92	10.0	14.6	23.4	9.11
4,000	3.00	16.1	24.5	39.6	15.7
5,000	4.24	23.5	36.7	59.3	24.0
6,000	5.64	32.1	51.2	82.6	34.0
7,000	7.15	41.8	67.9	109	45.6
8,000	8.84	52.7	86.8	139	58.7
9,000	10.6	65.2	108	173	73.4
10,000	12.5	79.0	131	209	89.7
12,000	16.5	110	184	293	127
14,000	21.1	146	246	388	170
16,000	25.9	186	314	496	219
18,000	31.2	231	389	614	274
20,000	36.7	280	473	747	335
22,000	42.6	334	563	889	401
24,000	48.9	392	661	1040	473
26,000	55.5	453	765	1210	551
28,000	62.0	520	878	1390	635
30,000	69.2	592	999	1580	723

\*Estimated Interaction Potential

TABLE XVIII (Cont'd )

BINARY DIFFUSION COEFFICIENTS FOR THE CONSTITUENTS OF AIR  
AT ATMOSPHERIC PRESSURE

Temperature (°K)	Binary Diffusion Coefficient, $D_{ij}$ ( $\text{cm}^2/\text{sec}$ )				
	(N <sup>+</sup> , O <sup>+</sup> )	(N <sub>2</sub> , NO)	(O <sub>2</sub> , NO)	(O, NO)	(NO, NO <sup>+</sup> )*
1,000	$5.87 \times 10^{-5}$	1.60	1.65	2.22	.657
2,000	$1.43 \times 10^{-3}$	5.09	5.15	7.44	2.02
3,000	$9.51 \times 10^{-3}$	10.2	10.0	15.2	3.91
4,000	$3.49 \times 10^{-2}$	16.8	16.1	25.3	6.25
5,000	$9.84 \times 10^{-2}$	25.0	23.4	37.1	8.99
6,000	0.227	34.5	32.0	52.1	12.1
7,000	0.453	45.4	41.8	68.7	15.6
8,000	0.805	57.6	52.7	87.4	19.4
9,000	1.31	71.5	64.9	108	23.5
10,000	2.00	86.5	78.3	131	27.9
12,000	4.04	120	108	182	37.7
14,000	7.12	159	143	242	48.5
16,000	11.1	202	182	309	60.4
18,000	16.3	251	226	382	73.3
20,000	22.5	305	274	465	87.1
22,000	30.8	363	326	553	102
24,000	40.5	427	383	650	118
26,000	52.7	494	443	752	134
28,000	66.7	567	509	863	152
30,000	84.1	646	579	982	170

\*Estimated Interaction Potential

TABLE XVIII (Concl'd)

BINARY DIFFUSION COEFFICIENTS FOR THE CONSTITUENTS OF AIR  
AT ATMOSPHERIC PRESSURE

Temperature (°K)	Binary Diffusion Coefficient, $D_{ij}$ ( $10^3 \text{ cm}^2/\text{sec}$ )				
	(e, N)*	(e, N <sub>2</sub> )	(e, O)*	(e, O <sub>2</sub> )	(e, NO)
1,000	1.58	1.49	7.80	2.92	2.19
2,000	4.46	2.90	19.6	7.43	4.46
3,000	8.19	4.65	31.0	11.7	6.21
4,000	12.6	6.64	42.0	15.4	7.51
5,000	17.6	8.90	52.8	18.4	8.81
6,000	23.2	11.2	62.6	20.3	10.5
7,000	29.2	13.8	72.3	21.8	12.8
8,000	35.7	16.4	79.6	23.5	16.2
9,000	42.6	19.0	86.5	25.6	20.7
10,000	49.8	21.7	94.4	29.3	24.7
12,000	65.5	26.6	107	38.5	32.4
14,000	82.6	30.8	120	48.6	40.9
16,000	101	34.6	133	59.3	49.9
18,000	120	37.4	147	70.8	59.6
20,000	141	38.9	160	82.9	69.8
22,000	163	40.7	178	95.7	80.5
24,000	185	42.1	195	109	91.8
26,000	209	43.5	214	123	103
28,000	234	44.9	235	137	116
30,000	259	46.3	256	152	128

\* Estimated Interaction Potential

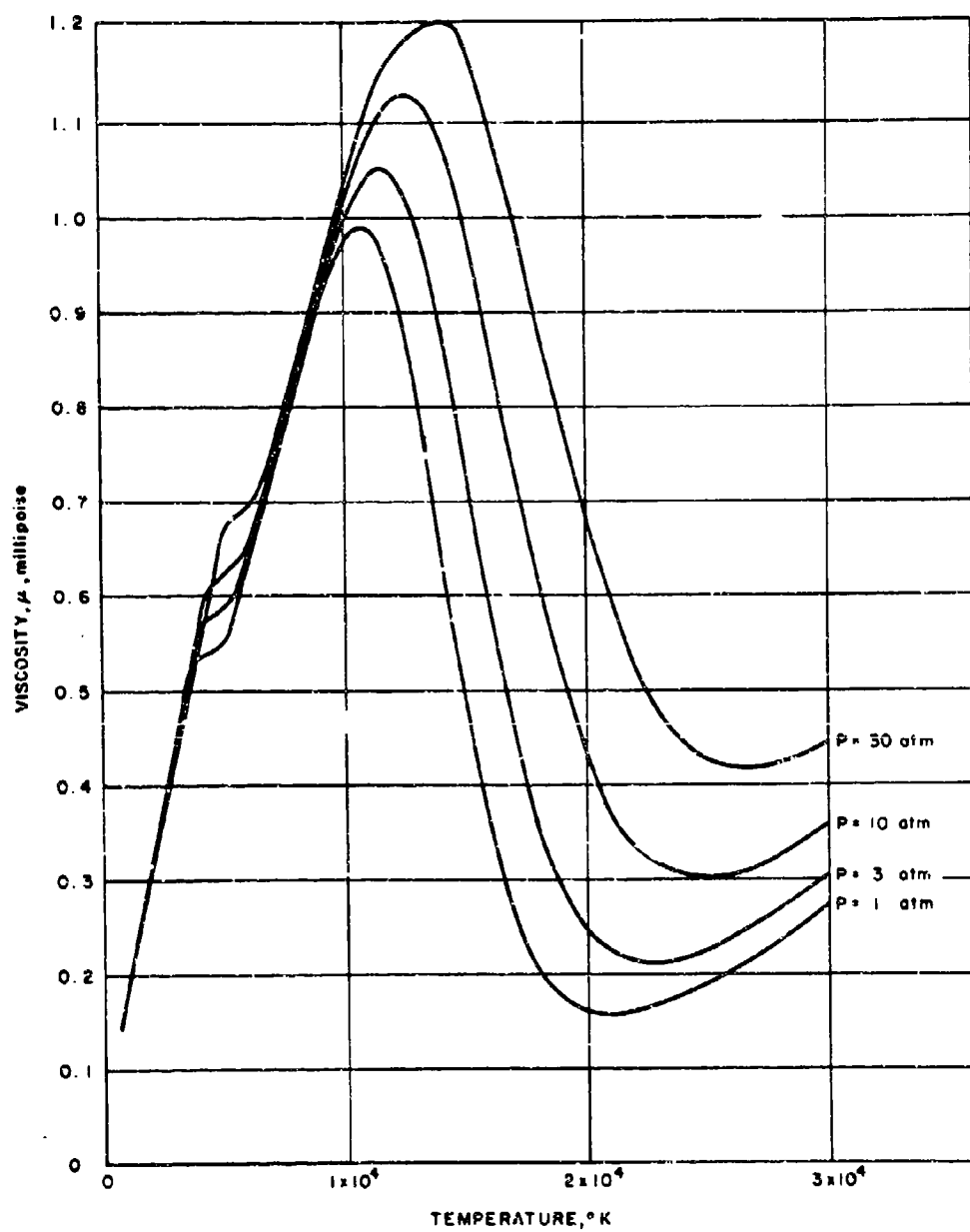


Figure 7 VISCOSITY OF HYDROGEN VERSUS TEMPERATURE  
62-1733

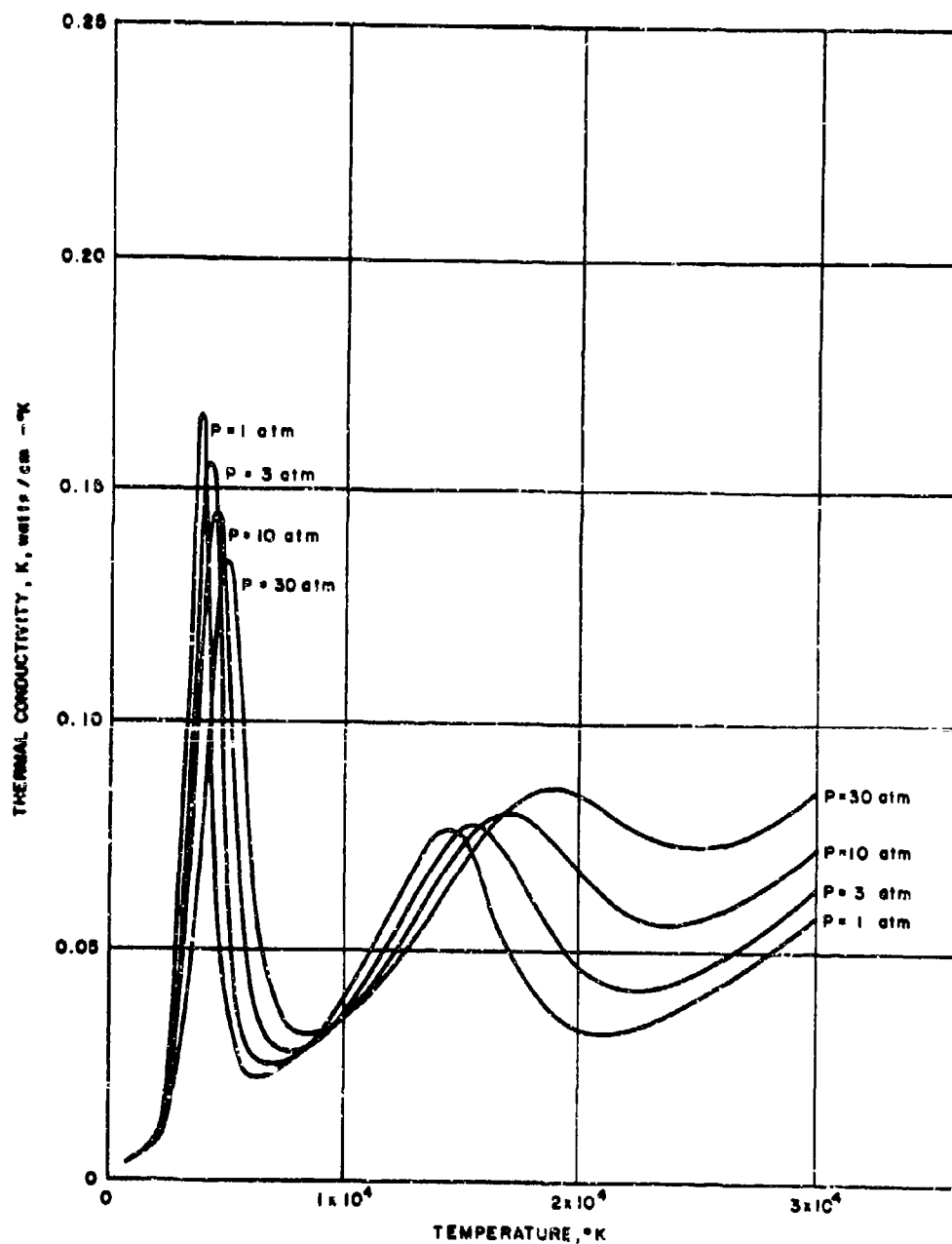


Figure 8 THERMAL CONDUCTIVITY OF HYDROGEN VERSUS TEMPERATURE  
62-1734



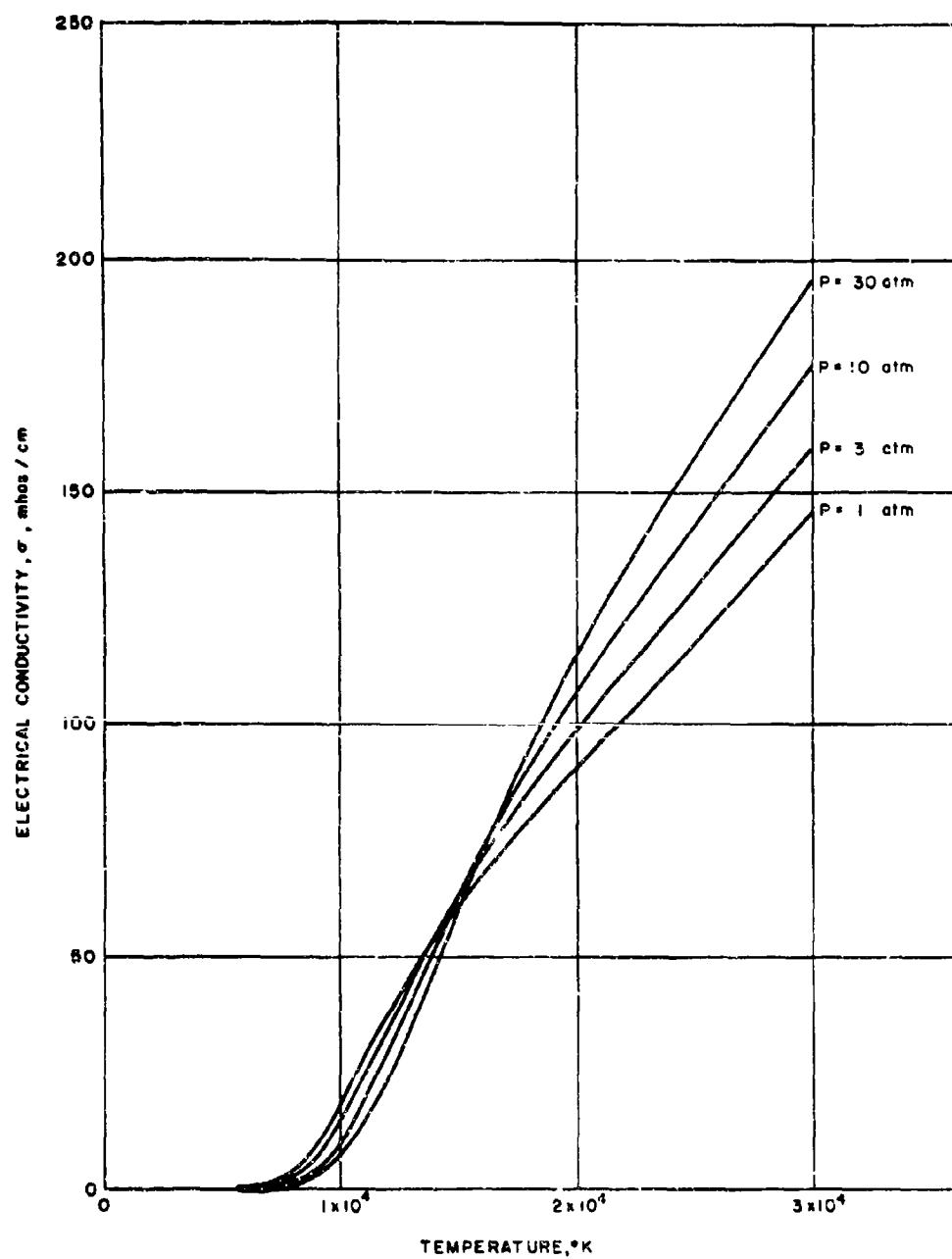


Figure 9 ELECTRICAL CONDUCTIVITY OF HYDROGEN VERSUS TEMPERATURE  
62-1735

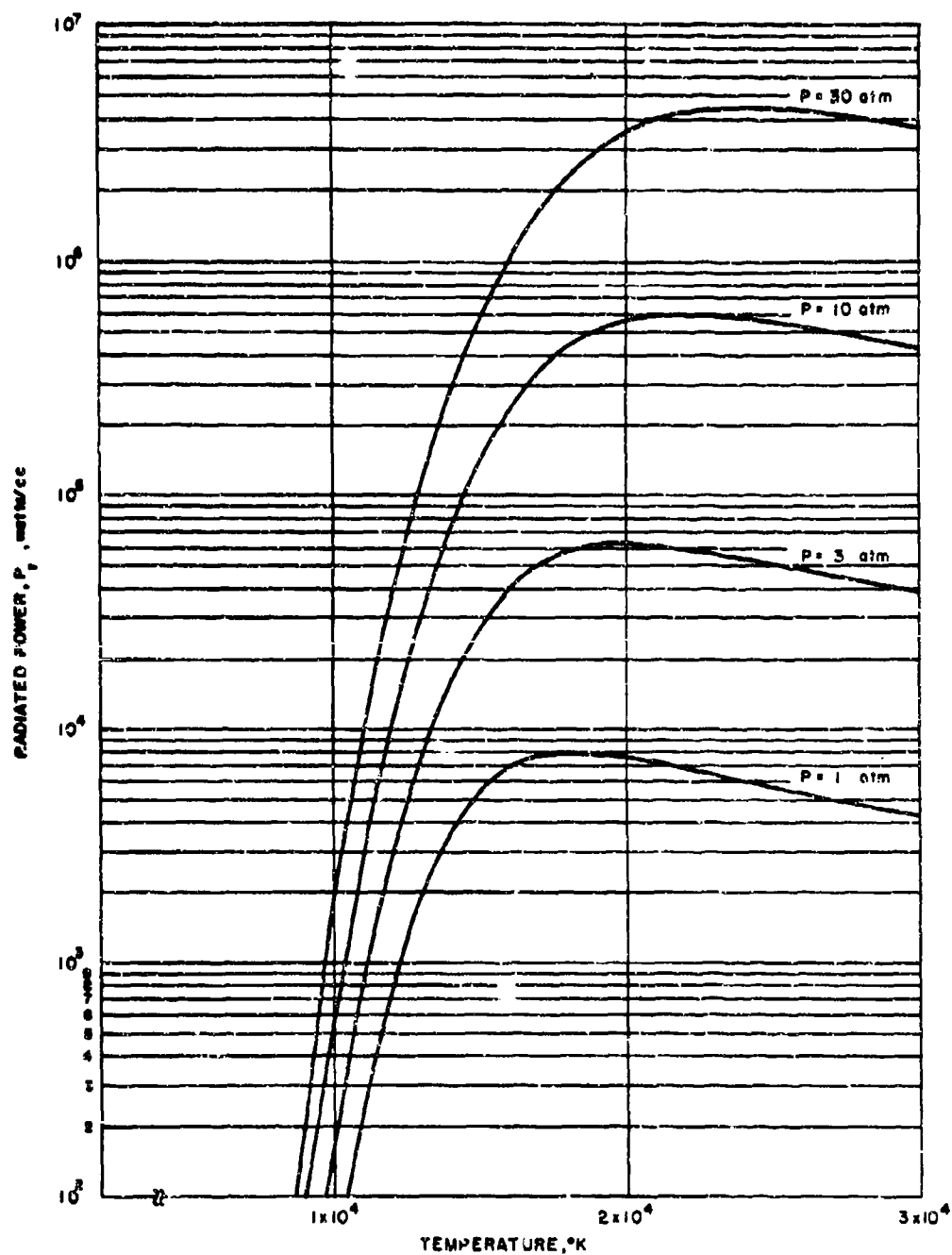


Figure 10 CONTINUUM RADIATED POWER PER UNIT VOLUME FROM  
HYDROGEN VERSUS TEMPERATURE  
62-1736

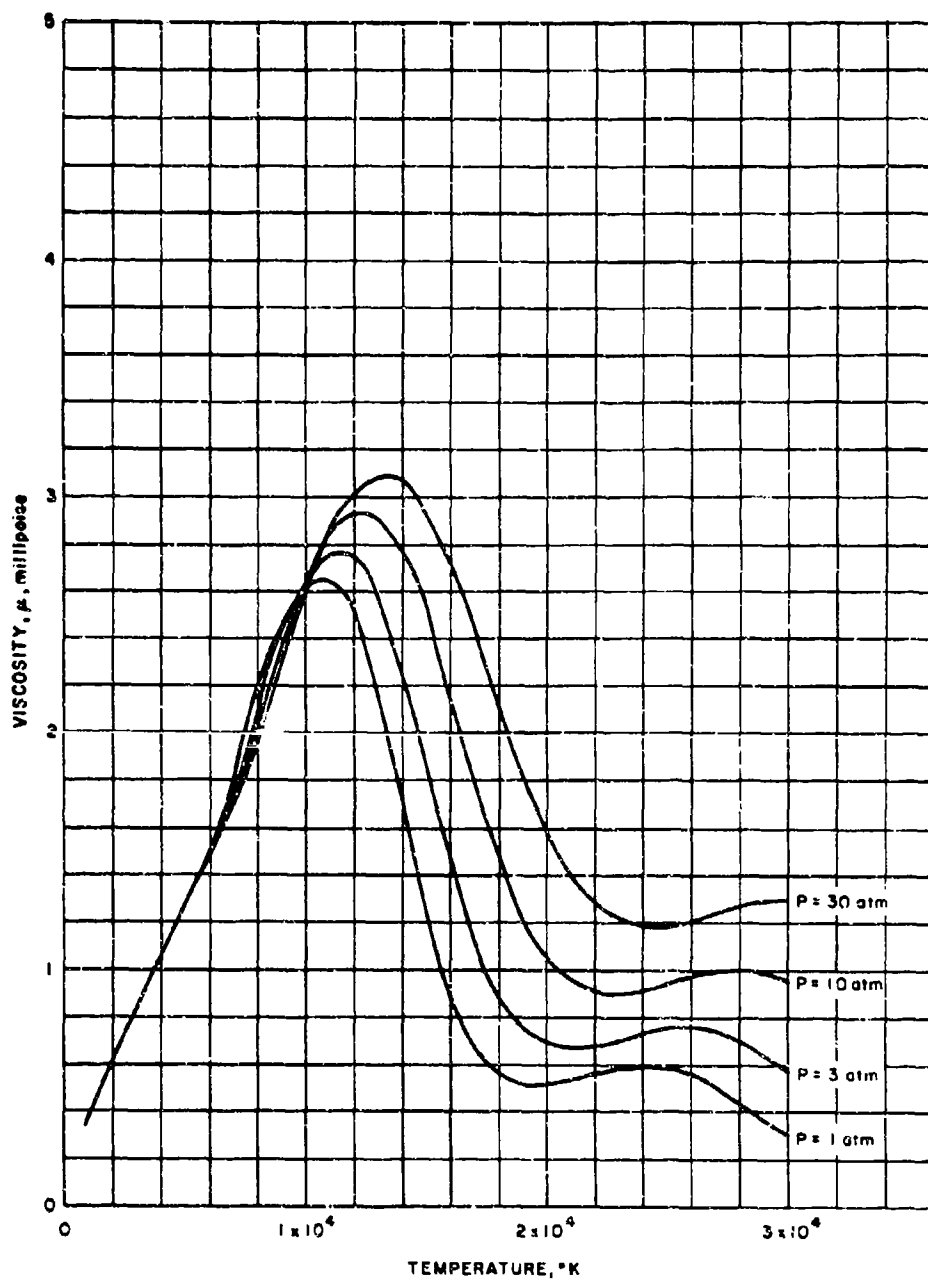


Figure 11 VISCOSITY OF NITROGEN VERSUS TEMPERATURE  
62-1737

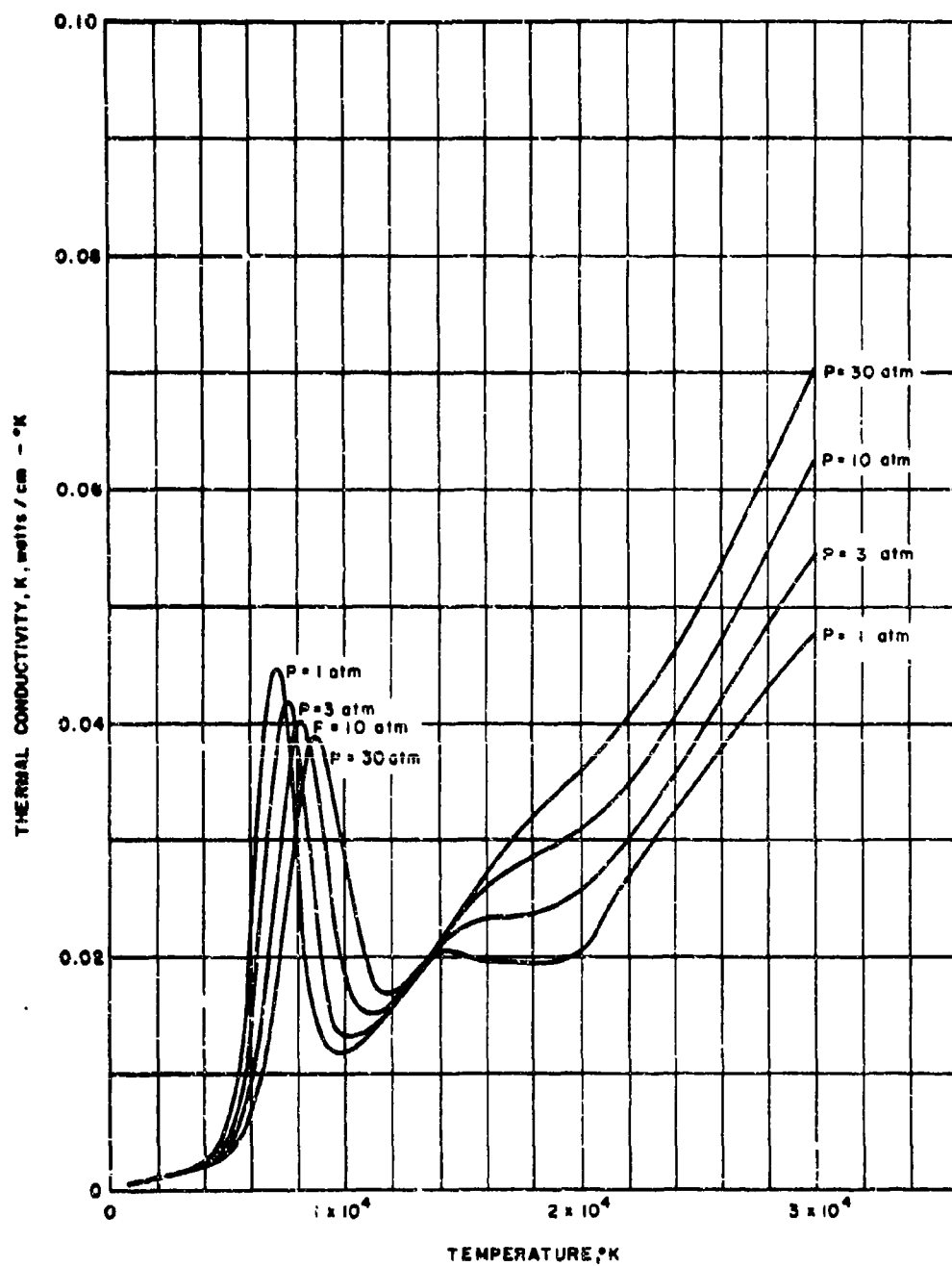


Figure 12 THERMAL CONDUCTIVITY OF NITROGEN VERSUS TEMPERATURE  
62-1738

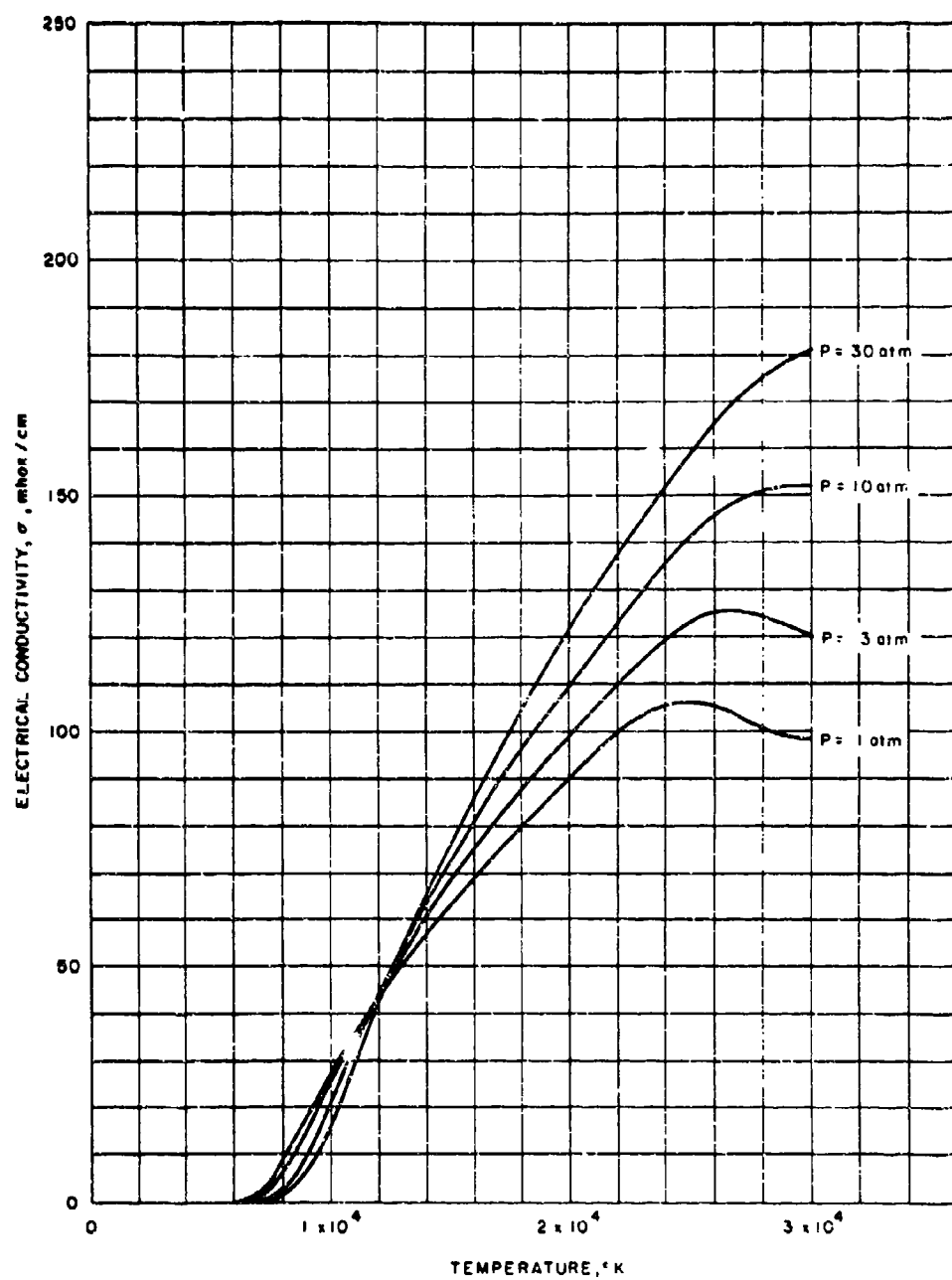


Figure 13 ELECTRICAL CONDUCTIVITY OF NITROGEN VERSUS TEMPERATURE  
62-1739

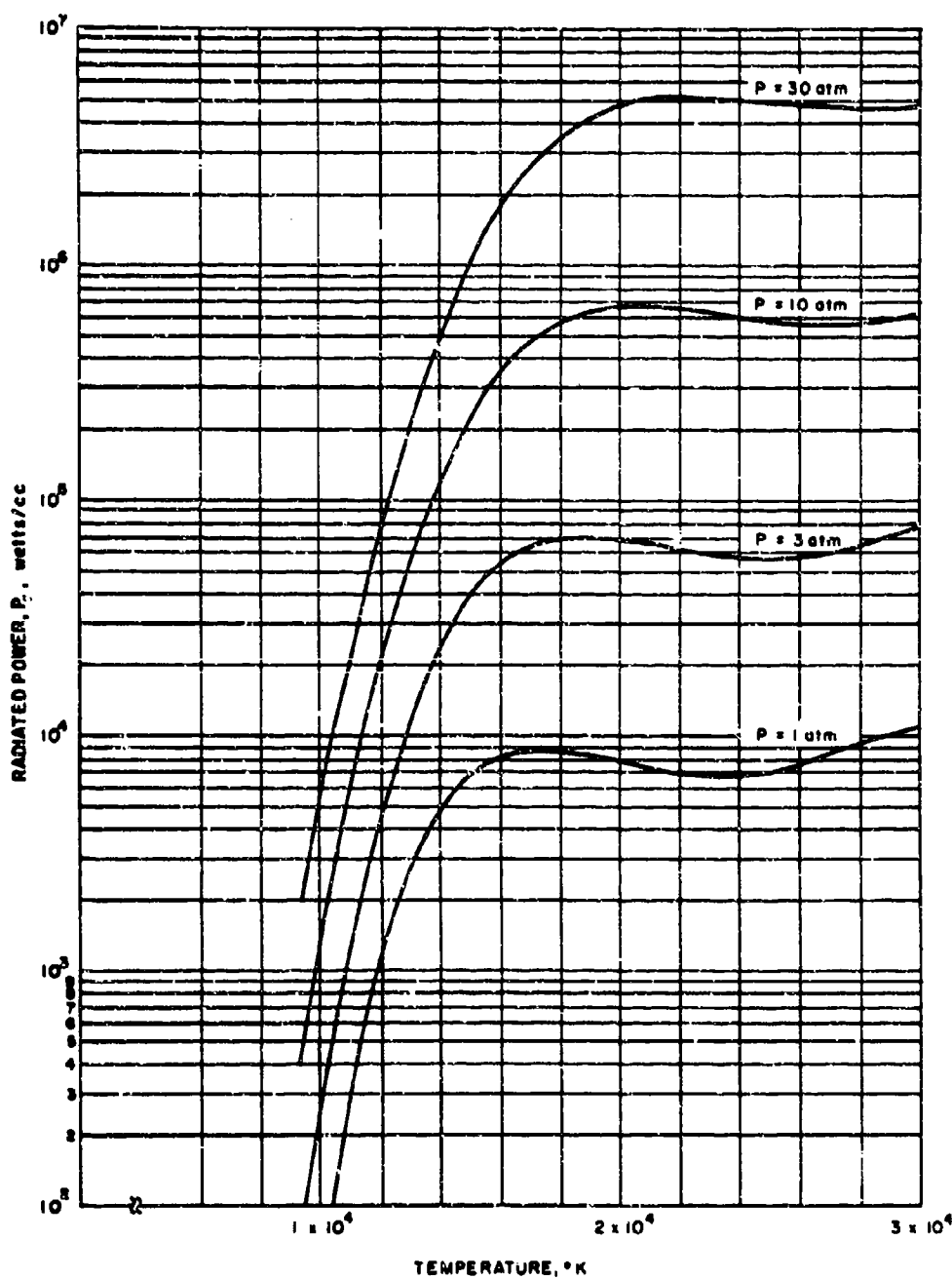


Figure 14 CONTINUUM RADIATED POWER PER UNIT VOLUME FROM  
NITROGEN VERSUS TEMPERATURE

52-1740

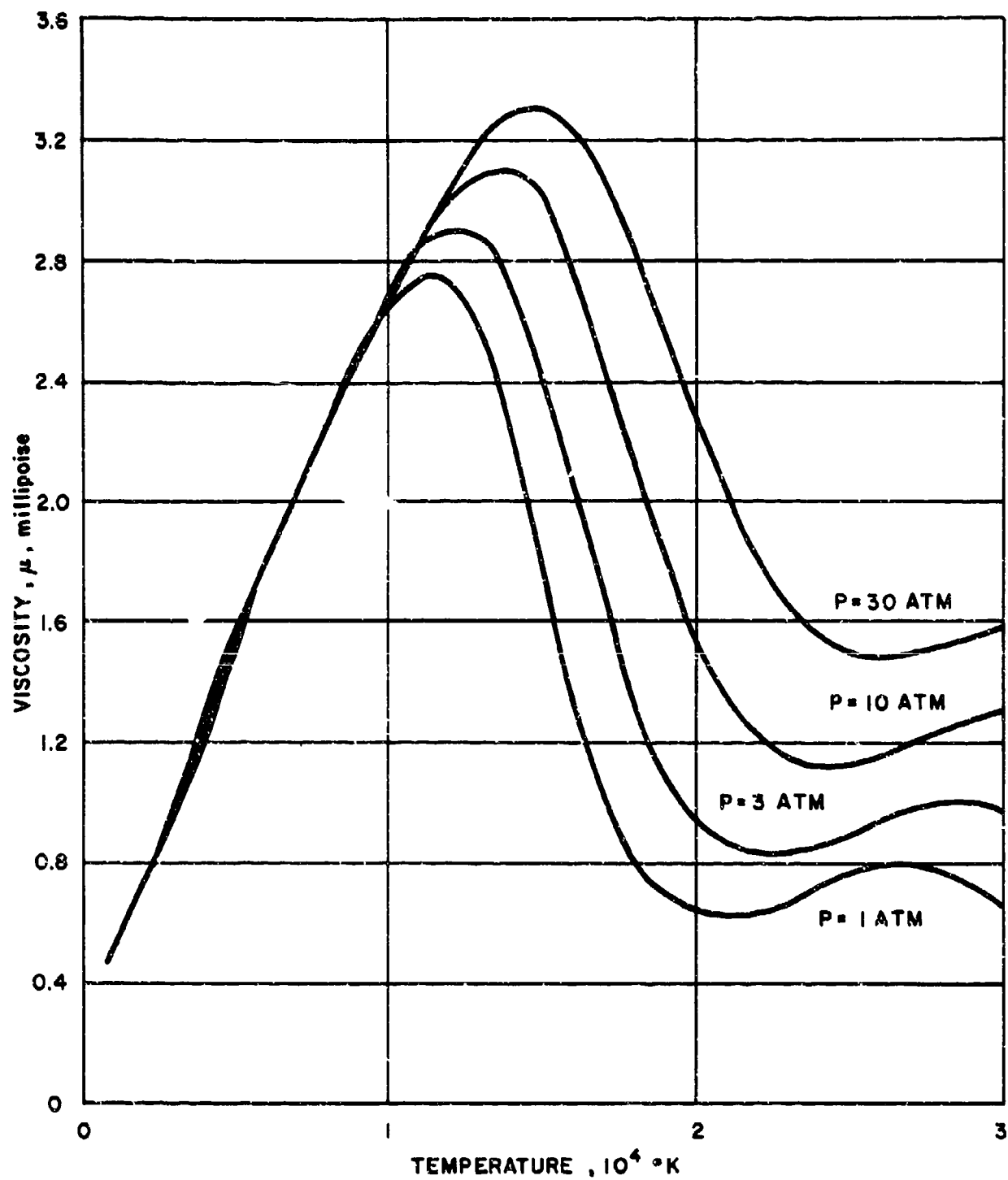


Figure 15 VISCOSITY OF OXYGEN VERSUS TEMPERATURE  
63-1999

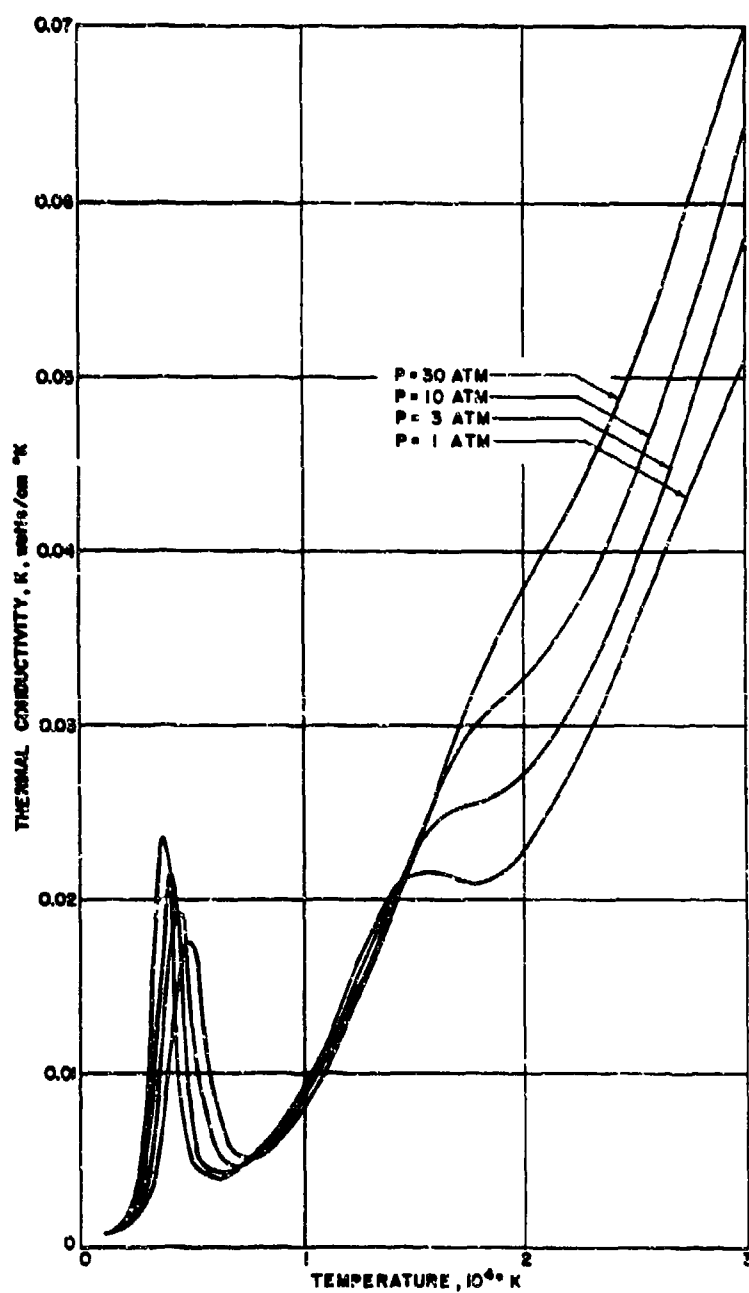


Figure 16 THERMAL CONDUCTIVITY OF OXYGEN VERSUS TEMPERATURE  
63-2000



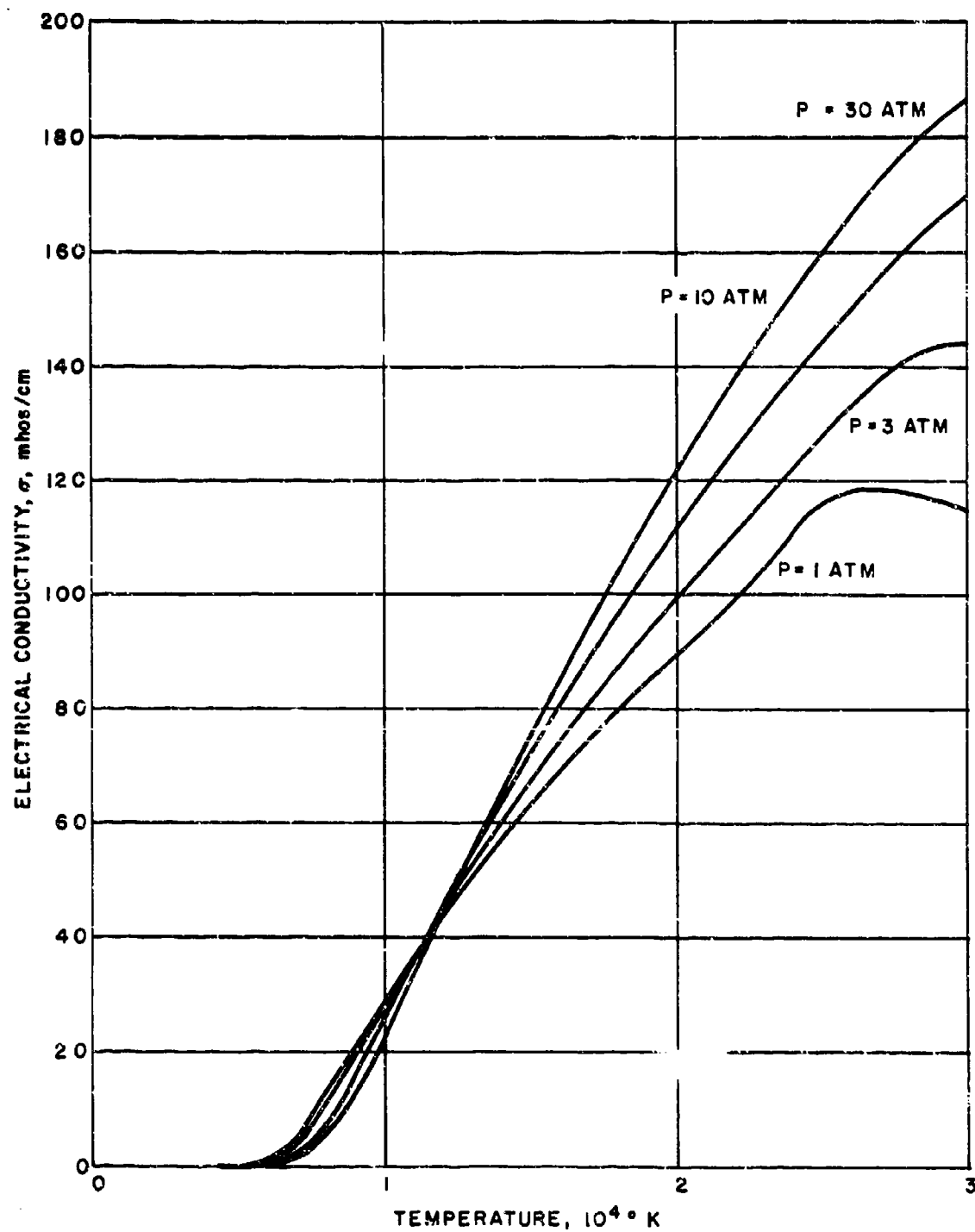


Figure 17 ELECTRICAL CONDUCTIVITY OF OXYGEN VERSUS TEMPERATURE  
63-2001

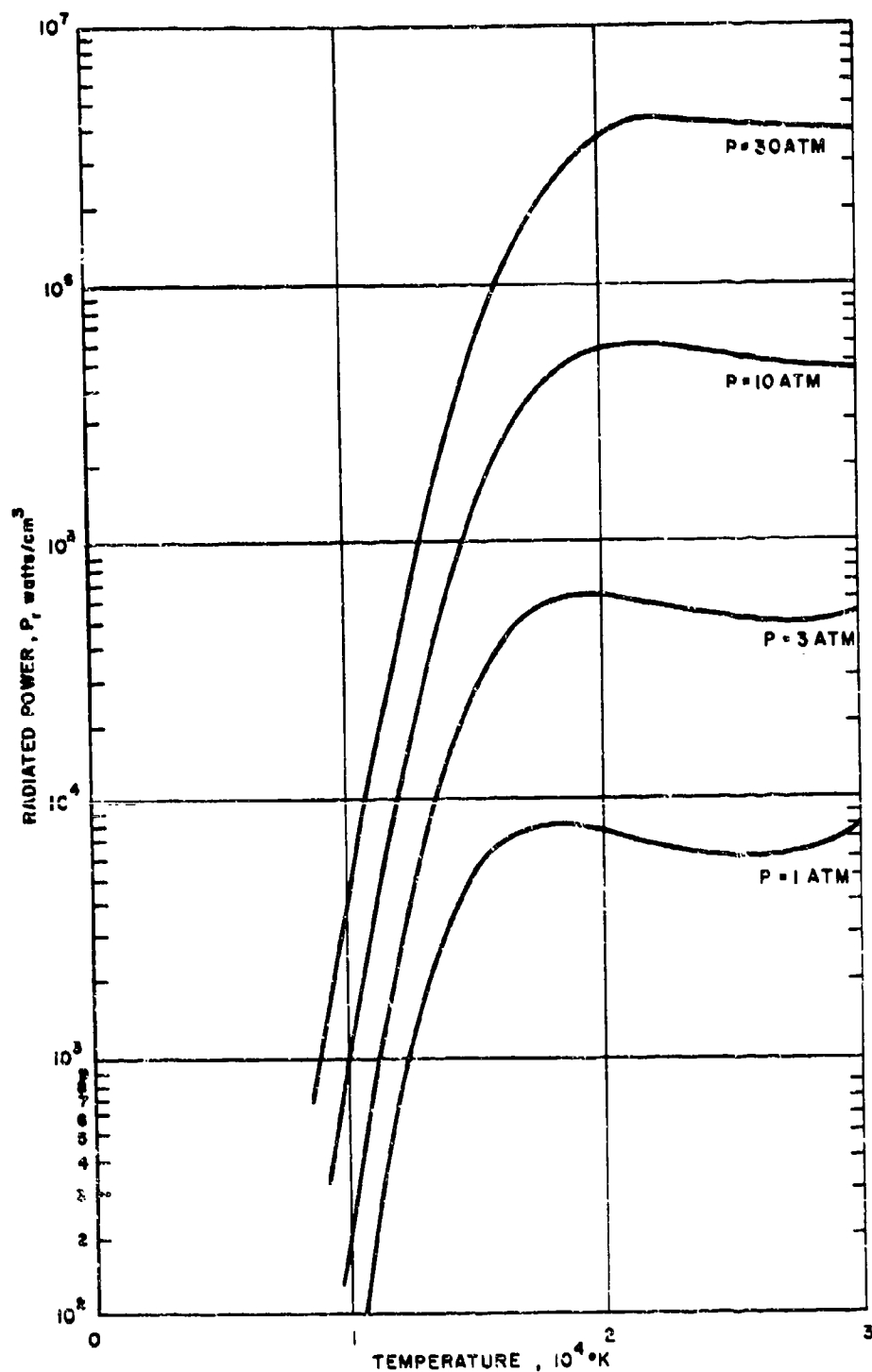


Figure 18 CONTINUUM RADIATED POWER PER UNIT VOLUME FROM OXYGEN  
VERSUS TEMPERATURE

63-2002

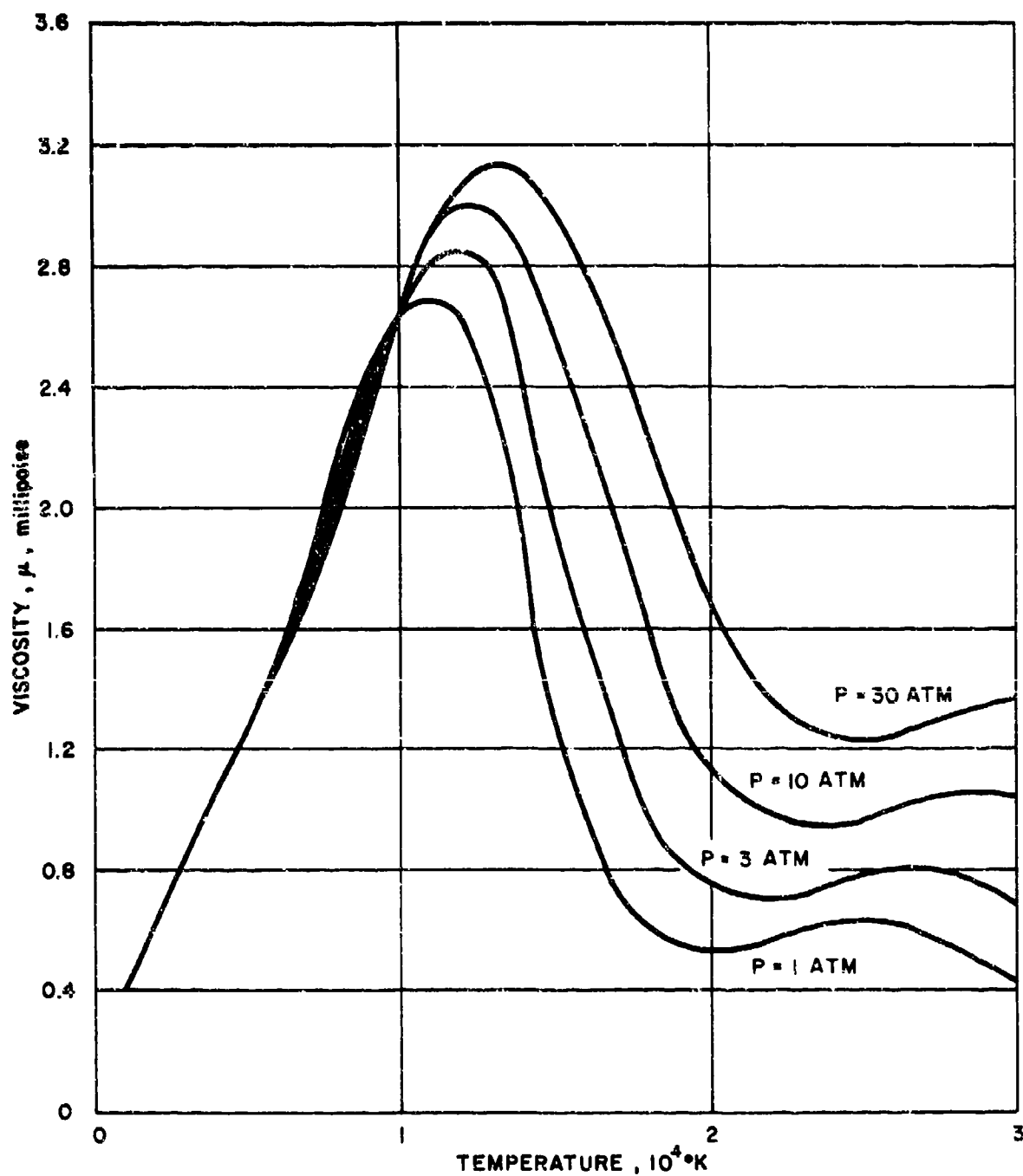


Figure 19 VISCOSITY OF AIR VERSUS TEMPERATURE  
63-2404

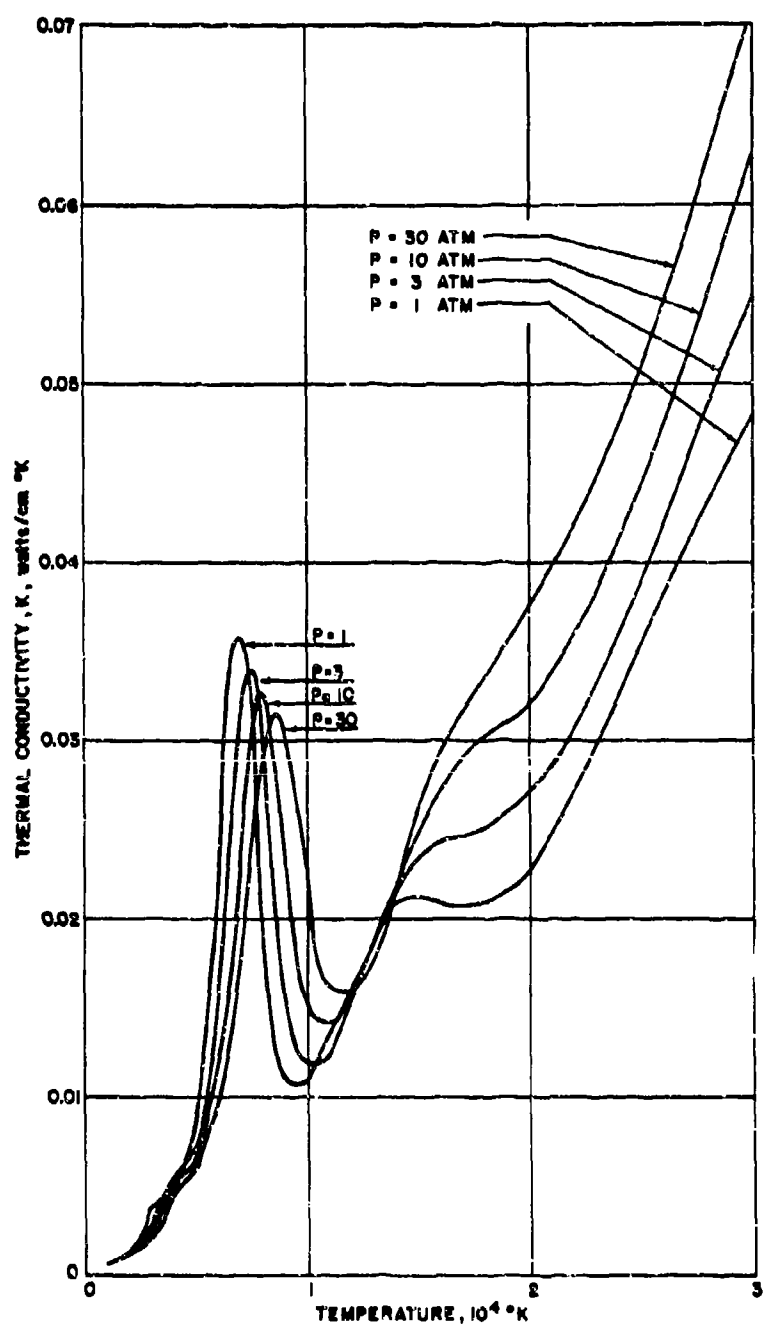


Figure 20 THERMAL CONDUCTIVITY OF AIR VERSUS TEMPERATURE  
63-2004

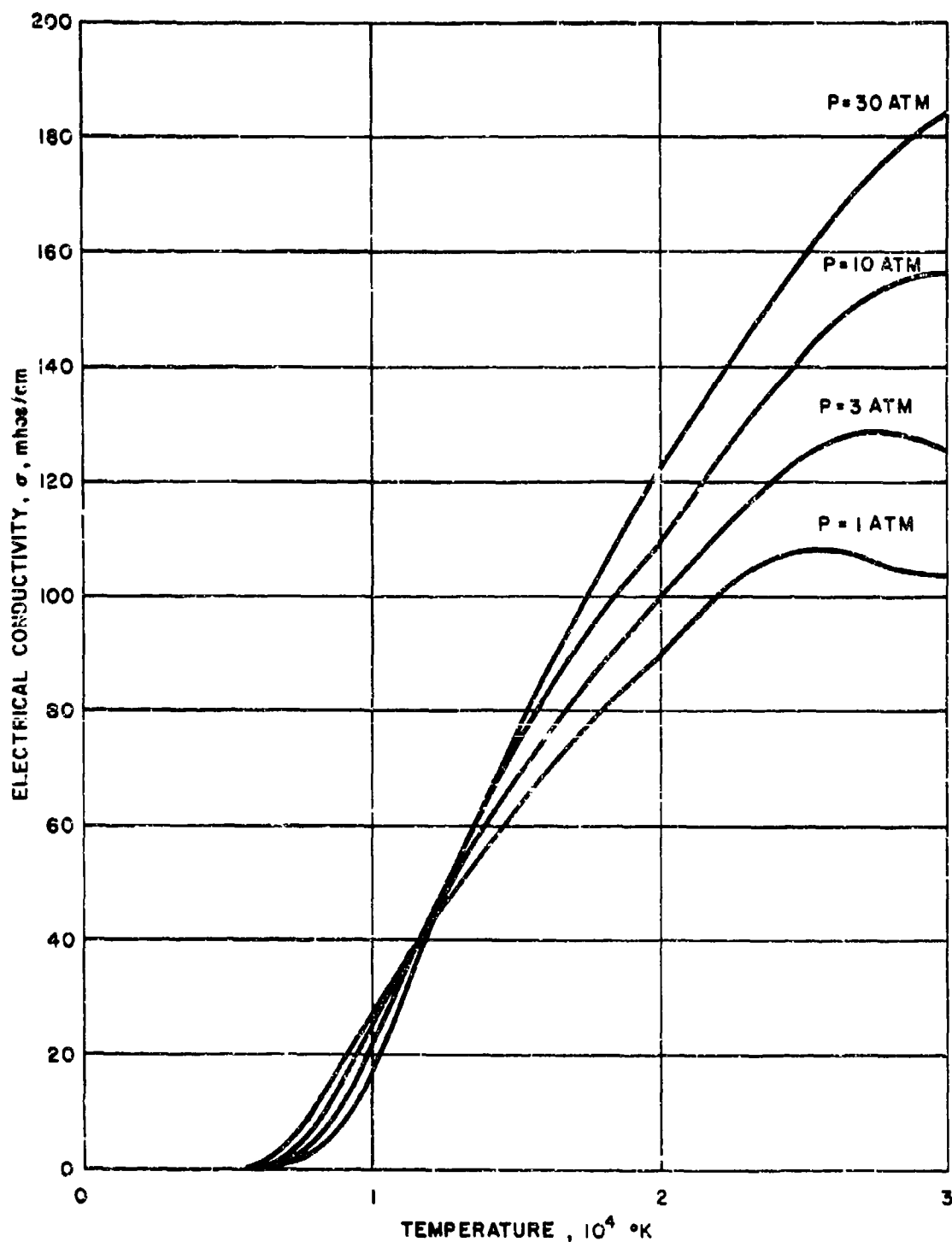


Figure 21 ELECTRICAL CONDUCTIVITY OF AIR VERSUS TEMPERATURE  
63-2005

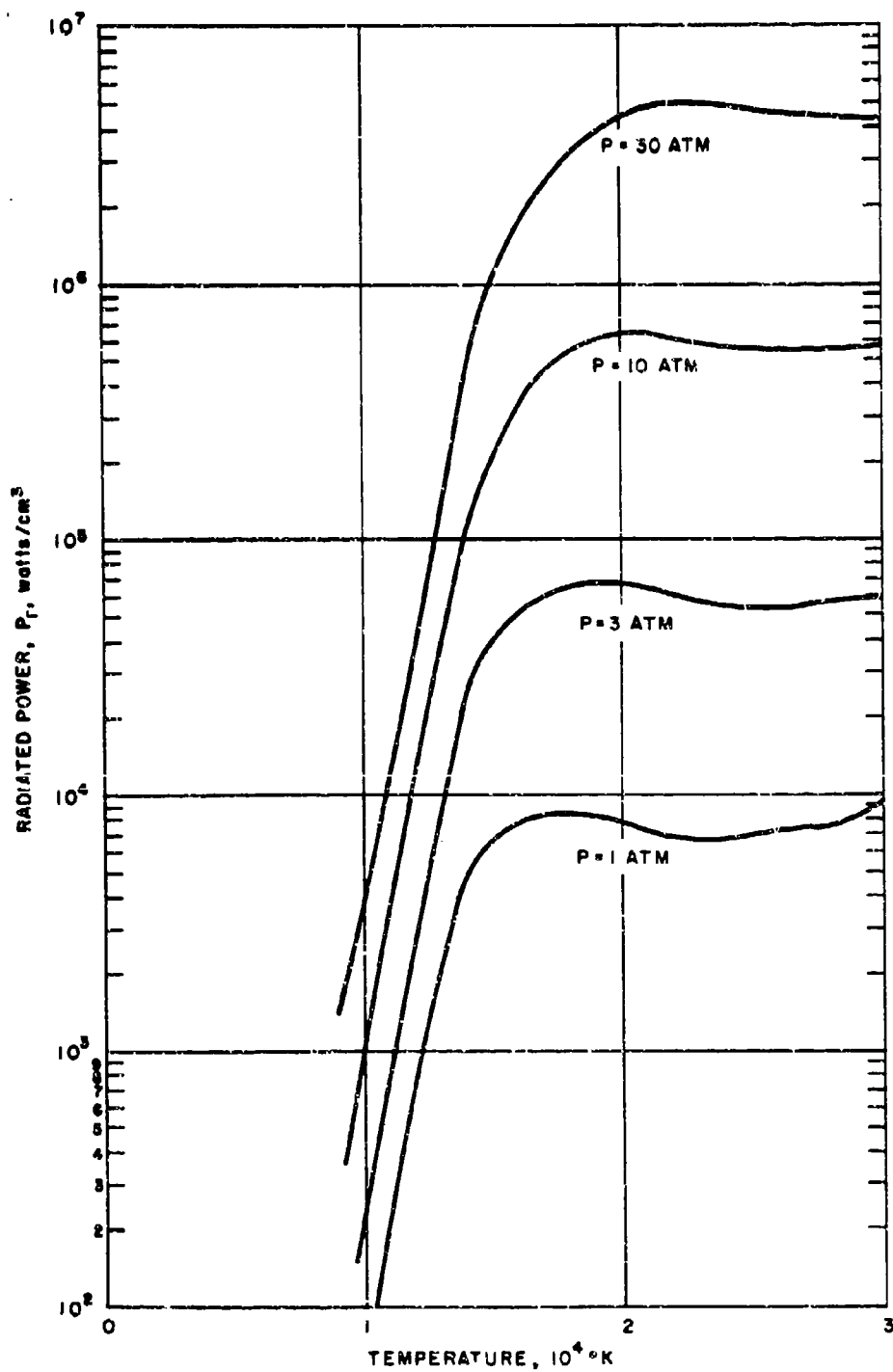


Figure 22 CONTINUUM RADIATED POWER PER UNIT VOLUME FROM AIR  
VERSUS TEMPERATURE

63-2006

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